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AT VULCAN'S SHOULDER: JAMES DWIGHT DANA AND THE BEGINNINGS OF PLANETARY VOLCANOLOGY

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ABSTRACT. J. D. Dana was a pioneering American naturalist who put an impressive stamp on four fields–mineralogy, zoology, volcanology, and geology–during a long career. Educated at Yale, the seminal event of his post-graduate education was participation in the United States Exploring Expedition in the Pacific between 1838 and 1842. Observations of atolls, volcanic islands, and active Hawaiian volcanoes, together with insights gained from the charting activities of the expedition, enabled him to make the first synthesis of volcanic action in the Pacific and to formulate the broader doctrines of the contrasts between, and the permanence of, continents and ocean basins, and of the historicity of the Earth.

The magnitude of Dana's contribution must be viewed from the perspective of geological sciences in the early 19th century. At the onset of the Exploring Expedition, direct accounts of volcanic action were scant, the Wernerian neptunist view of the aqueous origin of basalt had only just been laid to rest, most geologists still had no clear conception of how basalts erupted from volcanoes, fossil sequences were only beginning to be understood, and both geological mapping and systematic stratigraphy were in their infancy. Dana had little formal training in geology, but his observational skills were already evident in an early description of flowing lava and fire fountaining at Vesuvius (1835). Wide reading had made him familiar with current concepts of continental geologists. Dana was perhaps the first trained naturalist to observe the fluidal character of erupting basaltic lava, this at Kilauea on Hawaii, and he at once understood how this contrasted with the more viscid attributes of lava at Vesuvius. But he was also able to perceive how basaltic eruptions could build a large volcanic island, and to understand that fluvial action and subsidence eventually could reduce a Hawaii to an eroded volcanic stub, sustained as a land area only by the countergrowth of fringing and barrier reefs. Dana identified the linear arrangements of volcanic chains on the sea floor and established their age progressions using extent of erosion and development of offshore reefs. He predicted the existence of the vast tracts of drowned and deeply submerged atolls, now termed guyots, in the western Pacific, and said where they could be found.

Dana the geologist was unreservedly historical, a perspective that reflected his Christian opinion of the human estate as the culmination of Divine creation. The geological past was directed toward this moment no less than recorded human history, with a genuine beginning and substantive changes through time. This view contrasted with the uniformitarian (deistic) opinions of Hutton and especially Lyell, who saw processes repeated through an indeterminant length of time but no pattern of fundamental change. Dana's North American puritan tradition gave him the optimism that an Earth history could be established by human ingenuity and effort, and it persuaded him to devote

all his energies to this end. Dana entered the Pacific seeking broad patterns. The first of these he discerned was the interaction of volcanic action, fluvial erosion, subsidence, and coral growth on the islands he explored, leading to formation of atolls. This provided proof of direction in Earth history and a unifying planetary perspective, focused on volcanology, which was first outlined in Dana's report on Geology for the Exploring Expedition in 1849. Later, through voluminous writing and years of teaching, Dana carried these views to a position of extraordinary influence and importance for all subsequent geological science.

INTRODUCTION

The late E. Dale Jackson, whose own studies of Hawaiian geology and petrology have become landmarks, used to marvel at his nineteenth-century predecessor, J. D. Dana. In his talks, Jackson would show a slide depicting Dana's chart of the patterns of reefs, subsidence, and volcanic lineaments in the Pacific, which was published in 1849 as part of his report on geology for the U.S. Exploring Expedition (1838-1842). Jackson would point out several of the principal features of the chart, which Dana used to summarize his main conclusions concerning Pacific geology. These included: (1) documentation of the age progressions of several linear volcanic chains in the Pacific by means of comparative extents of erosion and development of reefs on older volcanoes; (2) parallelism of chains within the Pacific basin; (3) segmentation of volcanic chains, particularly the Hawaiian chain, where Dana distinguished the Loa and Kea trends; (4) delineation of regions of greatest subsidence in the Pacific and contrasting regions of uplift; and (5) distinction between orientations of volcanic chains in the subsiding portions of the Pacific and those, mainly island arcs, in uplifting portions of the Pacific near and along the Pacific rim. To Jackson, whose interest at that time was in the regional geology of the great Pacific linear volcanic chains, these were astonishing deductions, encompassing virtually all the critical observations necessary to the Wilson/Morgan hypothesis of plate motions over hot spots but more than 130 yrs before the fact. As if to seal his case, Jackson would mention Dana's seminal descriptions of eruptive phenomena at Kilauea and his contributions to fluvial geomorphology, which were largely based on study of a tropical volcanic island in the Pacific, Tahiti.

My intention is to outline how Dana came to develop so synoptic a view of volcanic action in the Pacific just by looking at islands and reefs. From this starting point, he went on to formulate a genuinely global synthesis which contrasted the role of continents and ocean basins and attempted to explain the formation of mountain ranges and continental crust throughout geological time. One of the great doctrines of Dana's synthesis, the permanence of continents and ocean basins, was based largely on conclusions derived from his explorations in the Pacific as a young man (Dana to A. Guyot, 1881, reproduced in Gilman, 1899, p. 331-332). How he came to this conclusion, and precisely what he meant by it, bear strongly on the course of geological thought in North America until the advent of plate tectonics. Even in the context of plate tectonics, some of his deductions are surprisingly prescient.

In 1972, when I first heard Jackson lecture, I was beginning my thesis work on the Samoan island group in the Pacific, which Dana visited during the Exploring Expedition in 1840. Dana's report describes general aspects of the physiography and geology of the islands but notes that here the age progression is in the opposite sense to that which he determined for the Hawaiian and Society chains. The island of Savai'i at the western end of the chain has a youthful, uneroded appearance, has had major historic eruptions, one of which Dana knew about from local accounts, and resembles Hawaii's Mauna Kea in that it is festooned with small volcanic cones. Successively more deeply eroded islands, Upolu and Tutuila, lie to the east, and a small atoll, Rose Islet, is at the eastern end of the chain. "It is apparent," wrote Dana, "that the fires were soonest extinct to the east, and have burnt longest, and to the latest period, on the westernmost island, Savai'i" (1849, p. 335).

Samoa made no sense in the framework of the Wilson/Morgan hypothesis, and I was attempting to figure out why. Eventually, with a combination of offshore marine surveys, aerial photographs, extensive sampling, petrochemical analyses, and radiometric dating, I was able to do this. But, mysteries of Samoa aside, none of these modern techniques were available to Dana in 1840, and in fact during the Exploring Expedition, he only managed a few weeks in aggregate of actual field work, on foot or horseback, in all the Polynesian islands he visited and only a few days at Samoa. He knew virtually nothing of offshore submarine geology. All the more justified, then, was Dale Jackson's astonishment at the scope of Dana's geological deductions about the Pacific.

My colleague, Professor R.N. Ginsburg, who co-convened this symposium on Dana, asks, on behalf of young students of geology: What made Dana the way he was? How was he able to accomplish so much, at a time when much of our science was in its infancy? The answers to these questions lie in an understanding of the youthful Dana, the choices he made about the type of scientist he would become, and the early influences on his career. The importance of the Exploring Expedition, on which Dana participated as a young man, was acknowledged both by himself late in life (Dana, 1889) and by later biographers (Gilman, 1899; Prendergast, 1978; Appleman, 1985, 1987). Clearly, Dana's conclusions about Pacific geology were well on his mind by the end of the Exploring Expedition. As a geologist, then, Dana already had his global perspective before he was 30 yrs old. Preparation of all the reports for the Exploring Expedition, when he began to expound his global perspective, dominated the next phase of Dana's career and figured strongly in much of the rest of his enormous body of work over the next 50 yrs. We must begin earlier than the Exploring Expedition, if we are to understand how all this came to be.

EDUCATION OF AN AMERICAN SCIENTIST

The thread I shall follow is Dana's interest in volcanoes, first fired by a visit to Vesuvius in 1834. At that time, Dana had completed three years of undergraduate study at Yale, largely under the eye of Benjamin Silliman, Professor of Chemistry and Natural History, founder and editor of the leading scientific journal in the United States, the *American Journal of Science,* and Dana's future father-in-law. At Yale, Dana completed what would be described today as a general liberal arts curriculum, including classical studies, with "courses in mathematics, rhetoric, logic, natural philosophy, moral philosophy, astronomy, chemistry, mineralogy, and geology. This curriculum was designed to provide the student with a broad foundation from which he could continue in the study of a profession such as the ministry, law, or medicine or pursue a career in agriculture, commerce, or manufacturing" (Prendergast, 1978, p. 23). A Yale education in the first half of the 19th century was clearly intended to be practical.

In his final year, Dana took Silliman's popular course in chemistry, mineralogy, and geology. But even including the young scientist's continuing countryside excursions in and around New Haven and work on collected specimens in Silliman's laboratory, which allowed him to hone a variety of technical skills, including drawing, Dana's exposure to geology as an undergraduate was undoubtedly far less than that of typical majors in geology today. His education, and thus his view of his own qualifications and credentials throughout his life, was as a naturalist, with sufficient skill to make broad scientific contributions on a range of topics, not just geology. Dana's systematic contributions to biology, mineralogy, volcanology, and geology thus all followed from an education in which the boundaries between these fields were not particularly well defined and which provided scientists, still few in number in the United States, with diverse skills suited to the needs of a growing nation with a large frontier in the early 19th century.

Dana first employment was as an instructor of mathematics to midshipmen in the U.S. Navy, which required him to participate in a voyage to the Mediterranean aboard the naval vessel *Delaware.* The voyage, with its stays at Minorca, the Greek Islands, and Italy, afforded Dana a variety of opportunities to pursue scientific interests, only one of which was his ascent of Vesuvius. At this point, there was still nothing particular in Dana's background or education that pointed strongly to a career in geology.

Dana's skills as a geological observer are nevertheless apparent in his description of Vesuvius in a letter to Silliman, which Silliman published as he tended to do with worthwhile correspondence, but apparently without Dana's knowledge, in *American Journal of Science* (Dana, 1835). Dana's account, despite the trepidation he evinces, is characteristically precise:

> *During the preceding few moments we had moved along with rather a hastened step, on account of the heat of the lava under our feet; for a red heat was frequently seen in many places within ten or twelve inches of the surface, and the rocks were yellow with an incrustation of sulphur. We were soon on the borders of what was apparently a fountain of melted lava, which, making its way from under the solid lava at the slow rate of a mile an hour, ran down the back side of the mountain towards Pompeii, not proceeding far enough, however, to injure an uninjured country. It resembled much a stream of fused iron. Its width was from four to five feet. From the form of the surface of the surrounding lava, I concluded that not long since its place of exit was higher up, and that by the solidification of its surface the change*

> *had been produced in the situation of its source, a process which now appears to be going on. We approached it within four feet. I cannot say that I felt disposed to try the experiment which Dolomieu states to be safe, that is, to walk on it,–the heat of the surface, as he says, not being sufficient to burn. It is certain that the reflected heat was sufficient to induce me to preserve the distance above mentioned* (from Gilman, 1899, p. 371).

The reference to Dolomieu, who saw Vesuvius some four decades earlier, shows that Dana was at least acquainted with summaries of European literature on volcanoes. Prendergast (1978) mentions the British Wernerian geologist Robert Bakewell's textbook, *Introduction to Geology* (1832), which provided such a summary, Scrope's *Considerations on Volcanoes* (1825) and Daubeny's *Description of Active and Extinct Volcanoes* (1826), which had appeared in serial form in *American Journal of Science.* But there was virtually no extant literature on volcanic phenomena by American geologists, and Dana was in select company among trained naturalists in the world who had actually seen an active volcano.

Upon Dana's return to Yale he commenced a systematic study of minerals which led to his first major work, the *System of Mineralogy: Including an Extended Treatise on Crystallography,* published in 1837. The *System,* which proposed an entirely new, and ultimately superseded, method of classification, might be considered the equivalent of a Ph.D. thesis today. Its publication secured Dana an international reputation, but by itself did not broaden his geological background. If anything, it indicated a predeliction to laboratory studies, systematization, and scholarly writing rather than field studies. The U.S. Exploring Expedition changed that.

With one travel experience under his belt, Dana knew that participation in this expedition, this time as a full-time naturalist, was an unexcelled opportunity. He had been asked to apply for a position as a participating scientist by Jeremiah Reynolds, chief lobbyist for the expedition, which had just been approved by the Congress (Prendergast, 1978). Once again, Silliman used his influence on Dana's behalf, writing a supporting letter. After Dana's position on the Expedition was secured, his brief–agreed upon at a preliminary meeting organized by Charles Wilkes, who commanded the enterprise–was to be responsible for geology, mineralogy, and crustaceans. Later, he took on corals. Unlike Darwin, who had sailed on the *Beagle* a few years earlier as sole naturalist, he had company. Six other scientists with different responsibilities and two artists were in the civilian party of this, the first scientific expedition funded, as it were, by the U.S. Navy.

Of all his responsibilities, Dana felt most deficient in geology, and he attempted to remedy this by the purchase of a number of books. Other works were sent to him during the expedition. Among these was Lyell's *Elements of Geology* (1838), which reached him at Valparaiso. This was actually a new and separately titled edition of the original volume 3 of Lyell's *Principles of Geology* (1833). The *Elements* contained Lyell's systematic application of actualistic or modern agencies of geological action to the past and his stratigraphic breakdown of Tertiary strata in Italy and France. It included an extended treatment of the volcanic history of Mt. Etna. Darwin himself had carried volume 1 of the *Principles* to sea with him and had volume 2 sent on when it was published. Curiously, after reading Lyell, Darwin was most enthusiastic about geology at the outset of his voyage (Browne, 1995) yet chose later to concentrate on organisms. Dana, less comfortable with geology at the beginning of the Exploring Expedition than other aspects of his training, kept fairly strictly to his brief in subsequent publications. This turned him to nearly a full-time career in geology as time went on.

The departure of the Exploring Expedition was delayed by nearly a year and a half. An important event in Dana's life during this wait was a personal conversion and dedication of the remainder of his life to Christ. One must not underestimate the importance of this on his outlook toward science and his approach to it. Personal conversion was an important component of Christian spiritual life in New England and upstate New York, where Dana was raised. It sprang from a rigorous puritan tradition which still remained strong in those portions of the young republic. Conversion was commonly prompted by revivals, one of which swept upstate New York, and involved members of Dana's family, in 1836. Religious ferment was not unusual in that part of the country. A few years earlier, Joseph Smith and associates founded the Church of Jesus Christ of Latter-day-Saints in western New York. Dana certainly knew the precepts of the leading revivalist of the 18th century, Jonathan Edwards, who himself graduated from Yale at the age of 17. At the time of Dana's conversion, Prendergast (1978) records, he copied out the words of Richard Baxter, described as a 17th century "puritan divine" (Perry, 1944):

> *. . . This day do I, with the utmost solemnity, surrender myself to thee. I renounce all former bonds that have had dominion over me; and I consecrate to thee all that I am, and all that I have; the faculties of my mind, the members of my body, my worldly possessions, my time, and my influence over others; to be all used entirely for thy glory, and resolutely employed in obedience to thy commands. . . .*

What this meant to Dana's life may be expressed in the words of Jonathan Edwards, describing the "practice of religion" of the Christian:

> *It may be said, not only to be his business at certain seasons, the business of Sabbath-days, or certain extraordinary times, or the business of a month, or a year, or of seven years, or his business under certain circumstances; but the business of his life* (Edwards, 1865, p. 314)

In *Puritanism and Democracy*, Ralph Barton Perry (1944) delineated some of the particular Calvinist roots of New England Puritanism and stressed how this came to be expressed in the economic virtues of prudence, zeal, diligence, and persistence, all of which could lead to worldly prosperity. This optimistic creed was well adapted to the commercial aspirations of the young nation in which Dana lived, and it was reinforced by Dana's practical education in the sciences. It provided a peculiarly American flavor and drive to Dana's work, which his European scientific contemporaries probably could little understand. From the point of his personal conversion forward, Dana dedicated his science to the glory of God and the spiritual betterment of the human race and pursued these aims with as much zeal, diligence, and persistence as he could muster. He set out to explore an earthly cathedral, and constantly saw divine majesty in whatever he observed. So it is recorded in many of his writings. He felt that, when all was said and done, science was a form of divine revelation, and that all theory would eventually be compatible with the hand of God. If this view in some cases led him astray scientifically (Gould, 1996), at the time of the Exploring Expedition it more probably led him on the search for the main themes of nature. It promoted his dedication to establishing a "world view," to looking constantly for the larger picture underlying the blizzard of detailed observations he was about to make. As a Christian, Dana could now make bold his science.

At this point in his life, however, Dana also had to reconcile modern scientific views of cosmology with Biblical revelation. The task may have been simplified for him by the fact that, in the religious tradition from which he and most Americans sprang, the right of private judgement was implicit.

> *The right of private judgement implies that the truth is accessible to the isolated individual. The individual who sees or represents the object as it is, possesses all that is necessary to truth–not the whole truth, but the quality of truth. . . . Beneath (Christianity's) specific cosmology and moral code there lay the deeper and more general presupposition of a common objective world and scale of values which reveal themselves to man through his cognitive faculties; or, if not through his natural intellect, then through the added light of revelation* (Perry, 1944, p. 282).

Among other things, this meant that Dana was not attached to a church with a formal doctrine on Creation, nor was he surrounded, as were Lyell and Darwin, by members of such a church. Instead, he was personally and socially free to make up his own mind about the meaning of biblical passages in the light of his own experience. To this point, his entire education convinced him that physical laws could be deduced from observation and analysis, and applied to the entire natural world. Becoming a Christian did not entail giving up this view, nor did it interfere with the course of his career. The social freedom Dana enjoyed in his religion meant, for example, that very little of the controversy that eventually raged in Britain over evolution touched him in his safe haven in Connecticut. This is not to say that Dana was without opinion on this controversy; indeed, decades passed before he agreed with Darwin and Wallace (Gilman, 1899; Prendergast, 1978). On this account, the scope of his difficulty with evolution and consequently of his response to it in publications was more personal and intellectual than it was influenced by pressure of public opinion (Gould, 1996).

Nonetheless, a Christian world view clearly colored one important aspect of his geology. Whether Dana had read Lyell before his conversion is uncertain, but he certainly did so not much later. Thus he had to be concerned with the great length of geological time that Lyell evoked and Lyell's one long argument, his "hundreds of worked examples," on behalf of actualism. Lyell, late in life, summarized his work as follows in a letter to Roderick Murchison:

> . . . *no causes whatever have from the earliest time to which we can look back, to the present, ever acted, but those now acting; and they never acted with different degrees of energy from that which they now exert* (Lyell, 1881, vol 1, p. 234).

This in part was simply a restatement by a geologist of Scottish philosopher David Hume's skeptical empiricism, and as a working method–a starting point–it was useful for any consideration of geological phenomena. But a world without the possibility of human enquiry detecting change was not acceptable to Dana. The extent of Lyell's skepticism was fully expressed at the end of the *Principles.*

> *To assume that the evidence of the beginning or end of so vast a scheme lies within the reach of our philosophical inquiries, or even of our speculations, appears to us inconsistent with a just estimate of the relations which subsist between the finite powers of man and the attributes of an infinite and Eternal Being* (Lyell, 1833, p. 385).

But this submissiveness went against the grain of Dana's evangelical Christian optimism. Whereas on the one hand, Dana certainly could see from Lyell's global survey that it was possible to view the Earth as a whole, on the other hand, as the type of Christian he was, as opposed to the Deist that Lyell was, he firmly believed that there is a destiny. This inclined him to the view that the Earth has a history, and eventually he expressed this in developing his geological history of North America. In an ultimate mimicking and repudiation of Lyell's *Principles,* the final edition of Dana's *Manual of Geology (1896)* has a long section on processes called "Dynamical Geology", which most of us would recognize as physical geology, followed by an even longer summary entitled "Historical Geology," beginning with Archean times and culminating in human history. The sequence from earliest to latest was deliberate, and the opposite employed by Lyell in *Principles of Geology.* The proper place to start a history is at the beginning, if one believes that there is a beginning and that successive historical events depend on what happened before. Lyell, however, traced Werner's system in working backward to successively murkier episodes of the Earth's past and came to the conclusion that nothing has changed significantly or at least that *we can't tell* that it has. Dana disagreed with this as a philosophical doctrine even before he sailed for the Pacific. Then and for the rest of his career, he viewed geological processes on the largest scale as being intrinsically historical, as having a beginning, a middle, and a modern end. His opinion was confirmed for the first time in the Pacific. Thus active volcanoes become inactive eroded volcanic stumps and eventually atolls. Time was not a cycle, but an arrow (Gould, 1987)–God's arrow to Dana–and worked in one direction.

Finally, Dana's Christianity bears on his eventual prodigious productivity–the thousands of pages of books and papers, his leadership as an educator and professional scientist, and his obvious ambition. Ralph Barton Perry characterized the puritan as a "moral athlete" in the following terms:

> *The puritan sailed his ship in the open seas. Despite his cult of moral vigor, he was not a moral introvert. He did not confine himself within his moral gymnasium, but used his strength out of doors, in the world. He pursued his calling, and he participated in the public life of his time and place. . . . From this school of discipline came men who were notable for doing what they soberly and conscientiously resolved to do, despite temptations and obstacles* . . . (Perry, 1944, p. 268).

This fairly describes Dana on the eve of his great voyage.

STATUS OF VOLCANOLOLGY IN 1837

Scientific study of volcanic phenomena at the time of departure of the Exploring Expedition was just barely at a point where even the most basic processes were at all understood. Systematic scientific accounts of volcanic eruptions were in their infancy and mainly concerned Vesuvius. One of the most important and useful accounts, written to the Roman historian Tacitus some two decades after the fact, was actually that of Pliny the Younger who described the climactic episode that destroyed the ancestral summit (Somma), as well as the cities of Pompeii and Herculaneum, and killed his uncle in 79 A.D. The younger Pliny was only 18 yrs old at the time.

> *On the 24th of August, my mother desired (my uncle) to observe a cloud which appeared of a very unusual size and shape. . . . He immediately arose, and went out upon a rising ground from whence he might get a better sight of this very uncommon appearance. A cloud, from which mountain was uncertain, at this distance (but it was found afterwards to come from Mount Vesuvius), was ascending, the appearance of which I cannot give you a more exact description of than by likening it to that of a pine tree, for it shot up to a great height in the form of a very tall trunk, which spread itself out at the top into a sort of branches; occasioned, I imagine, either by a sudden gust of air that impelled it, the force of which decreased as it advanced upwards, or the cloud itself being pressed back again by its own weight, expanded in the manner I have mentioned; it appeared sometimes bright and sometimes dark and spotted, according as it was either more or less impregnated with earth and cinders* (Pliny the Younger, from Tappan, 1907, p. 394).

The precision of description, despite what turned out to be an extraordinarily hazardous personal experience, presages Dana and was not to be matched by any other remotely scientific account for centuries. The *Encyclopedia Britannica* article on Vesuvius records "Between 79 and 1631, reports with a scientific background are occasional and poor." A long course of Roman decline and European recovery intervened. Serious observation of Vesuvius began in earnest with persistent observations by Sir William Hamilton between 1772 and 1783, establishment of an observatory in 1812, and descriptions by Scrope and Lyell, which Dana may have read, or read of, in reviews. Dolomieu, Gay-Lussac, von Buch, and Humboldt were among the notable naturalist/geologists who visited Vesuvius prior to Dana.

The question of whether basalt was igneous in origin or a precipitate from sea water was still being debated into the 1820's (Laudan, 1987; Dean 1992). The Wernerian, or Neptunian, hypothesis of the aqueous origin of basalt was not so beyond possibility as it now seems. At this time, before hand lenses came into common use, geological mapping was in its infancy. It was largely developed by Werner and his students (Laudan, 1987), yet field criteria for identification of intrusive and extrusive basalts in many types of outcrops were still not understood. So featureless a rock as compact and oftimes altered basalt was not so obviously different in kind from graywacke or shale, especially if it was interstratified with them in the same succession.

The field interpretation of basalt as flowing lava could not be verified on the European continent, which lacks an active basaltic volcano–more strictly, an active tholeiitic basaltic volcano. The two most active volcanoes, Vesuvius and Etna, today are erupting mainly ash, scoria, and thick scoriaceous lava flows like the andesitic one Dana described or the alkalic ones of the crater, Valle del Bove, at Etna's summit which Lyell described in his *Elements of Geology,* and which Dana (1849) compared to Hawaiian craters. Great tracts of flat-lying or conformable basalts at various locations in Europe could not be explained by phenomena at these volcanoes. Even the huge basaltic Laki fissure eruption in Iceland in 1783, which was described in accounts published in Denmark as early as 1784, did not receive sufficiently wide scientific notice to dislodge Wernerian opinions about basalt. Apparently, accounts written in Icelandic and published as booklets in Denmark were not widely read. Werner's own views on the aqueous origin of basalt, for example, were published in 1786 and again in 1789. No leading European naturalist witnessed the Iceland eruption nor soon went to Iceland to study its products. This is surprising in that some effects of the eruption were immediately evident in Europe. It dropped ash as far south as Venice (Thoroddsen, 1914, 1925) and produced such a hazy and extremely cold winter in Europe that even Benjamin Franklin (1784) took time from his diplomatic duties in Paris to describe it (Sigurdsson, 1982). The consequent famine in Iceland *was* noted in a widely read journal (DeLamanon, 1799). Eventually, Lyell, in volume 1 of his *Principles* [1830], used the original accounts (Hólm, 1784; Stephenson, 1785) and corroborations (Pálsson, 1784; Mackenzie, 1811) to provide a thorough summary of the molten Laki flow ravaging the countryside, coursing down steep stream beds, and cascading over escarpments. But by this time the debate over basalt was over, and Lyell used this information for other purposes. The one natural event, and a huge one at that, that could have decided the question at the outset was either overlooked or ignored until it was irrelevant.

Perhaps the most significant argument for an igneous origin for basalt at the turn of the 19th century coincided with the birth of experimental petrology. The experiments of Sir James Hall (1805), which were designed to test arguments of James Hutton, showed how typical basaltic textures could be produced by varying cooling rates and indicated the very high temperatures needed to produce molten basaltic lava. At the time of Hall's experiments, the sources of heat for volcanic eruptions were variously ascribed to underground reactions between sulfur and pyrite, the burning of buried coal seams (Desmarest, 1774; Werner, 1789), which was no doubt prompted by some actual experiences in mines, or strongly exothermic reactions involving reaction of ground water or sea water with oxidized metals in sedimentary rocks, as proposed by Sir Humphrey Davy in 1806 (Davy, 1828; Siegfried and Dobbs, 1968). This latter view was favored in two of the sources on volcanic processes with which Dana was certainly familiar (Daubeny, 1826; Bakewell, 1832). Volcanic phenomena were thus viewed by most continental geologists as local phenomena, fueled by shallow heat sources.

The view of Hutton (1788, 1795), of course, was that there were heat sources of much larger scale within the Earth, and that these were intimately bound with volcanic processes. This was only just beginning to receive wide currency in the first quarter of the 19th century. Crystalline rocks, meaning most plutonic (for example, granitic) and metamorphic rocks, had been classified by Werner as "primitive," meaning lowest in stratigraphic succession (that is, "oldest"). But like the more obviously sedimentary strata above them, they precipitated from sea water. In contrast, Hutton viewed marble as being compacted and recrystallized limestone and slate as recrystallized shale. Water, chemists had shown, was incapable of dissolving siliceous minerals. Thus granites, gneisses, serpentinites, slates, and basalts could not have precipitated from it. Heat, not water, was responsible for the compactness, texture, and crystallinity of these rocks. The great elevations of many such rocks required forces acting within the Earth, and these required heat.

Wernerians did not accept much of this (Dean, 1992). Hall's experiments went far toward establishing great heat, not sea water, as being required to form granite and basalt. Still, it is fair to say that not even in the decade before Dana began at Yale was the issue put to rest. Most of the few scientists practicing geology in North America in the first decades of the 19th Century were still firmly Wernerian in outlook (Laudan, 1987). The first geological map of the United States, for example, was produced by a Wernerian, William Maclure, in 1809 and revised in 1818. Prendergast (1978) notes that Jeremiah van Rensselaer, in *Lectures on Geology* (1825), described Hutton's theory as "improbably hypothesis" and thought that eventually "accumulated evidence will weigh in favour of the aqueous origin of most rocks." Prendergast (1978) also records Silliman in 1842 recalling a discussion he attended between Neptunists and Plutonists in Edinburgh in 1805/06:

> *In imagination we were plunged into a fiery Phlegethon, and I was glad to find relief in the cold bath of the Wernerian ocean, where my predilections inclined me to linger.*

However, even in 1842, long after Werner was discredited, Silliman would only admit to a partial conversion.

The leading volcanological theory of the time was that of "elevation craters," conceived by Leopold von Buch, a student of Werner's. Even though by this time (1820) most geologists including von Buch admitted to the volcanic origin of basalt, von Buch still did not see how steep-sided, symmetrical volcanoes, like Somma, the volcano whose summit was destroyed at Vesuvius in 79 A.D., could form from thin ribbons of basaltic lava. For example, even though the Laki eruption produced a series of small volcanic cones along the main fissure (and these were the sources of the ash which reached Europe), the main lava extravasations did not produce a large conical volcano like Vesuvius. von Buch became convinced that a great deal of the substance and shape of such a volcano is produced by intrusion, which uplifts and tilts stratified formations radially away from the centers of intrusion. True volcanoes, or "craters of eruption" like Etna and the one currently built on the remnants of Somma at Vesuvius, in von Buch's view were simply surficial structures on the tops of punched-up ruptures in strata. Like modern Vesuvius, they rest within, or on, the "elevation craters." The tilted strata typically include sedimentary rocks interbedded with basalts (for example, Etna), which von Buch, in an updated conception of Wernerian doctrine, considered to have erupted under water.

Large basaltic islands in the ocean basins, like Tenerife and especially La Palma in the Canary archipelago, which von Buch visited in 1815, were also touted as examples of elevation craters. In the Canary Islands, for example, lava flows of various compositions are commonly interbedded with conglomerates (Schmincke, 1976), although both facies are now considered subaerial, and La Palma has a spectacular gorge heading from a cirque-like amphitheater–the presumed elevation crater–even then termed "Caldera" (Lyell, 1830). Although Lyell attacked this theory on both theoretical and observational grounds, modern studies actually lend it some credence. For example, there are uplifted marine sedimentary and submarine volcanic formations in both the Canary and Cape Verde Islands (Schmincke and Staudigel, 1976). At La Palma, manifestly uplifted pillow lavas (termed the Seamount series), which erupted under water but about which von Buch knew nothing, occur 600-m above sealevel in the floor of the gorge just described (Staudigel and Schmincke, 1984). These adjoin an intrusive gabbro-syenite plutonic complex located precisely in the valley amphitheater, just where von Buch would have had it. The pillows are intruded by numerous sills, which Staudigel and Schmincke, in a modern reprise of von Buch's hypothesis, consider to have contributed significantly to their uplift. Paleomagnetic studies confirm that the pillow lavas of the Seamount series were successively tilted as they were intruded (Gee and others, 1993).

von Buch's theory held sway among many geologists for the next 30 to 40 yrs (Laudan, 1987). It was covered extensively, for example, in Daubeny's (1826) textbook, which Dana read. Darwin (1844) considered that a number of volcanic islands in the ocean basins (St. Helena, Mauritius) had, indeed, formed over craters of elevation. He, too, believed that basaltic lavas could not consolidate on a steep slope. Notably, however, neither Lyell nor Scrope ascribed to it. Lyell (1830), in particular, went to some pains to describe how neither Etna nor La Palma and Tenerife in the Canaries are craters of elevation. He debated the issue with von Buch and Élie de Beaumont before a large audience in Bonn in 1835 (Laudan, 1987), but in the following year von Buch was as unrepentant as ever (Buch, 1836). Suffice it to say that by the time Dana entered the Pacific, he was both familiar with the theory of elevation craters and some of the controversy that surrounded it. He would also discover that the hypothesis of craters of elevation was directly at odds with his major conclusions regarding subsidence of volcanic islands in the Pacific.

In summary, there really was just enough known about volcanic phenomena in 1838 so that Dana was not seriously handicapped by huge gaps in knowledge or gross misconceptions. Much of what was necessary for him to know, however, and which allowed him a large canvas for speculation, had been concluded, or was still being debated, by the group of geological naturalists active one generation ahead of Dana. These men–Hall, von Buch, Gay-Lussac, Humboldt, Daubeny, Davy–were in fact contemporaries of Silliman. Charles Lyell, though somewhat younger, was seasoned by extensive field experience and had already made his massive contribution to geology. As young and inexperienced as Dana was, he had read or knew of the works of all these scientists. And he carried with him the vivid experience of Vesuvius to color his impressions as he traveled the Pacific. Vesuvius was also a counterpoint when he eventually came to Hawaii and viewed flowing basaltic lava for the first time, which none of these other men had ever been able to do.

We can also consider Dana's situation in the terms of Thomas Kuhn (1962). There was as yet no global perspective on volcanic phenomena, no paradigm uniting all the observations which Dana could only just then, for the first time in the history of the science, reasonably trust as scientifically accurate. Hutton and Lyell had framed a world view which, for all its breadth, was still based mainly on the study of western European sedimentary outcrops. Dana then sailed out to spend four years in a totally contrasting environment on the opposite side of the globe. The Pacific was a grand anomaly, and to incorporate it in the framework of his own thinking, Dana had to develop an utterly new, and necessarily global, concept of the Earth and its history. Dana shifted the Huttonian and Lyellian paradigm, itself only recently established, to one that included volcanic processes acting on a vast scale, one that also attributed major features of the Earth's surface to internal forces that were expressed by volcanism and had changed systematically through geological time.

DANA IN THE PACIFIC

Embedded in the larger report on Geology, which encompassed all of Dana's geological observations during the Exploring Expedition, is a treatise on volcanic action in the Pacific. This treatise consists of four chapters (III-V and VII), treating successively the Hawaiian, Society, and Samoan volcanic chains and then the summary chapter. The chapters are closely linked to observations on coral reefs, especially the atolls of the Tuamotus, presented in chapter II. The sequence of chapters III-V is clearly deliberate, first to present a discussion of volcanic action where it can actually be observed, then to compare the Hawaiian archipelago to the next most similar chain, the Societies, then to present Samoa as somewhat of a departure–but not a great one from the other two chains. The grand conception is to link construction of volcanoes from the eruptive stage to their partly simultaneous, but largely subsequent, history of erosion, encirclement by reefs, subsidence with the reefs surviving to form atolls, and then disappearance beneath the waves.

But in fact Dana observed this sequence almost precisely in the reverse order. He drew his deductions from a sequence of observations obtained almost in the manner of the opening of a set of nested Chinese dolls, one enclosing the next, with the first one, the atoll, representing the final, completed product of a long series of processes, and the innermost most precious and important one, Hawaii, representing the beginning. Travelling from southern Chile, the expedition first encountered the atolls of the Tuamotu group, then the Societies, then Samoa. The Fiji Islands, New Zealand, Antarctica, and Australia intervened, then the ships reached Hawaii. At some point in this sequence, Dana came to his encompassing visualization. He may have realized a part of it at Sydney, Australia, where he chanced to read a newspaper account of Darwin's newly published theory of coral reefs. Nevertheless, the full solution to the puzzle came at Hawaii, which he thus places first in his treatise. He had observed numbers of islands, each similar enough to some other island to be placed in a sensible sequence and perceived as single stages of geological works in progress. The Hawaiian islands had everything.

> *Among the groups of Polynesia, the Hawaiian exceeds all others in geological interest. The agency of both fire and water in the formation of rocks, is exemplified not only by results, but also by processes now in action; and the student of nature may watch the steps through the successive stages. He may descend to the boiling pit, and witness the operations in the vast laboratory, with the same deliberation as he would examine the crucible in a chemist's furnace. Thus the manner in which mountains are made, and islands built up, becomes a matter of observation. . . .*
>
> *While these volcanic mountains are still extending their limits, in one part of the group, in others, those changes are finely illustrated which they undergo through the action of water, gradual decomposition, and other allied causes. . . . In (some instances) they are altered in every feature, the heights worn down, the whole surface gorged out with valleys. . . .*
>
> *Moreover, the coral formations of the shores present us with reefs now in progress from the growing zoophytes. . . .*
>
> *The group is consequently the key to Polynesian Geology. It combines all the features which are elsewhere widely scattered, and they are so exhibited in progressive stages as to afford mutual illustration. An island like Tahiti, so broken into peaks and ridges, may excite wonder and doubt. The Hawaiian Group suggests the same difficult problem as Tahiti; but an intelligible solution is at the same time presented for our contemplation and study* (Dana, 1849, p. 155-156).

The Exploring Expedition offered some considerable advantages. First, there were six ships involved, and their practical task was surveying. Commander Wilkes commonly employed all six vessels in a typical coastal survey, arranging them in specific patterns for measurements of distance and triangulation (Ehrenberg, Walter, and Burrough, 1985). An apt comparison might be the modern-day multi-ship oceanographic expedition or experiment, where simultaneous positions of vessels moving in designated patterns must be precisely recorded throughout. No previous expedition, not those of Cook, nor Bligh, nor Necker, nor that of Fitzroy and Darwin aboard *Beagle,* was carried out on such a scale. During the Exploring Expedition, a typical island survey would involve moving the ships systematically around the island, and in some cases dispatching shore parties for mapping and altimetry. This was the constant work of almost everybody. It was arduous and exacting; it extracted its toll in exertion and fatigue but produced charts of such quality that some of them were used up until the Second World War. As a consequence, Dana's basic descriptions of volcanic islands are full of precise information about altitudes, slopes, dimensions of features, depths of bays, and soundings showing the limits of offshore banks and reefs. The radial pattern of valleys at Tahiti was apprehended not only from a difficult and inspiring climb of a knife-edge ridge to the highest point on the island but also from circumnavigation of the island and the surveying of its coast. The acquaintance with locations of volcanic centers, either as pairs or along *en* *echelon* segments of a volcanic chain, came from careful attention to charts which were constantly being prepared or modified as the daily work of the expedition.

Shore parties were commonly sent in several directions. Dana's report frequently makes use of notes and journals compiled by his fellow scientists and by Wilkes himself. On Hawaii, Dana saw Kilauea; Wilkes ascended Mauna Loa. At Tahiti, Dana's party traveled up one valley and fellow scientist Joseph Couthouy's another. Dana constructed a description of the central amphitheater on the island from his and Couthouy's notes (Appleman, 1985).

One aspect of the geology of volcanoes in the Pacific also worked to Dana's advantage. They are, for the most part, simple structures and leave striking impressions. No great leap of imagination is usually required to link cause and effect. This might not be obvious in reading Dana's descriptions, as vivid as he tried to make them. However, to someone who has trodden the same paths, been to the same islands, Dana's accounts are astonishingly accurate, and his deductions are in accord with everyday experience. For example, Dana is considered a founder of fluvial geomorphology. To become a fluvialist, all one has to do is ascend a large Tahitian valley and get caught in a rainstorm. An immediate sensation is of the ferocity of attack of water on rock. Playfully splashing pools become raging torrents, large boulders become dangerous projectiles, waterfalls emerge on formerly dry cliffs, and rocks cascade from unseen heights, reaching the valley floors in clattering crescendos. During a large storm, bridges are washed out, trees are undercut and washed away, and the courses of streams in the alluvium at river mouths are completely rearranged. Even on a clear day at the coastline, streams supplied by the virtually unending orographic rain at the mountain summits typically discharge huge quantities of reddish brown silt into the salty lagoons. The barrier reef at Tahiti is broken systematically where each river dumps its load into the lagoon (Darwin, 1842; Deneufbourg, 1965). At these breaks the bulk of the stream load is carried past the reef into the deep sea. In his summary chapter, Dana compared the great radial gorges of Tahiti with the fluted surface of Oahu's Diamond Head, saying that both were produced by the same process, erosion in the one case by streams and in the other by rivulets. This is obvious to anyone who has seen them both.

Dana's most significant deductions regarding stream valleys were to recognize both their characteristic shape, a narrow gorge widening to a steep-sloped but wide, cuspate, amphitheater at the top, and that the streams come to grade at sealevel. Some of them, such as Tahiti's Papenoo and Punaruu, even meander through the coastal alluvium. ". . . through . . . undermining and denuding . . . the *narrow bed becomes a flat strip of land between lofty precipices* (emphasis Dana's) through which, in the rainy seasons, the streamlet flows in a winding course" (Dana, 1849, p. 387). Steep ravine side slopes ascending for hundreds, or even more than a thousand, meters, require long, deep gorges, with the stream paths themselves rising hundreds, or more than a thousand, meters to headwaters in the amphitheaters. No other process Dana could discern produces such steep, scalloped slopes. In contrast, faulting on volcano flanks tends to result in straight and very steep cliffs (for example, southeastern Upolu in the Samoan Group; Dana, 1849, p. 325).

When Dana saw similarly scalloped and steep topography on an island remnant centered in a lagoon, but without the streams to produce it (for example, at Tahaa, Raiatea, and Bora Bora in the Societies) and the lagoons and coastal sedimentary deposits protecting the cliffs from the seas, he had to conclude that the rivers and streams were once there, but that they have subsided, and the former stream mouths are now hundreds, or more than a thousand, meters below sealevel, buried by sediments in the lagoons. Deeply embayed islands (Moorea–Dana's Eimeo–in the Societies; Tutuila, in the Samoan Group), have not so greatly subsided. The lagoons surrounding all these islands are bounded by barrier reefs, the corals of which have kept pace with the subsidence, as Darwin said. The lagoons are wide to the extent that the volcanic remnants are low and submerged. The widths in fact define the approximate original stream lengths. Characteristic stream slopes coupled with the distances between reefs and volcanic remnants give a rough estimate of the extent of subsidence. In this way, Dana linked an original volcanic structure, hundreds or more than a thousand meters high and circular or at least simple in plan, with an equally simple, radial drainage system, to a succession of ruggedly mountainous and embayed islands, smaller volcanic stumps with wide barrier reefs, and then atolls. Darwin (1842) outlined a similar sequence but not one so closely tied to the fluvial modification and stages of reduction and subsidence of the volcanoes. In addition to Darwin's simple distributions and shapes of fringing reefs, barrier reefs, and atolls during the stages of island reduction by erosion, Dana provided an *independent* criterion for evaluating subsidence. More than this, Dana took the same sequence and, identifying the stages of subsidence of successive volcanoes in a group, and their relationship to offshore reefs, established their age progression.

Dana's observations of the active volcanoes of Hawaii made the most striking impression on his mind. In the report, he first considers the simple domed shape of Mauna Loa–the low slopes and large proportions relative to the summit crater. Immediately he points out that this is quite unlike the common conception of a volcano, and he laments the exaggerations of slope in typical sketches or artistic renditions even of a steep-sided volcano like Vesuvius. At Kilauea, which was then merely stirring around and producing lava cones and fountains, he noted the comparative stillness of the desolate scene, stating that, in contrast to Vesuvius, there was scarcely the noise to drown out a normal conversation. But let Dana express it.

> *The very stillness of the scene impresses the mind with a sense of mighty powers only temporarily at rest. No "subterranean thunder" rolled through the depths of Pele; no "raging sea tossed its billows into fiery spray;" no deep gulf threw up showers of stones and cinders . . . this repose is, perhaps, more fearfully sublime than the fitful heavings of a Vesuvius* (1849, p. 176).

Fire fountaining to heights of 60 ft might be spectacular, but Dana knew that this was nothing compared to the thousands of feet often attained at Vesuvius. The two volcanoes are fundamentally different. More dramatic

Hawaiian eruptions and caldera activity than Dana witnessed, such as occurred at Kilauea in 1824, including a lava flow 8 miles wide reaching the sea (Ellis, 1842), were still characterized by the fluidal properties of the basaltic lava, which Dana immediately understood to reflect both lower viscosity and less water than at Vesuvius. The lavas themselves carry only crystals of olivine (chrysolite) rather than the myriad of minerals, including augite, amphibole, and leucite, in Vesuvian lavas (that is, they are tholeiitic rather than shoshonitic). Dana recapitulates the descriptions of Ellis and others about shifts of level in the lava lake at Halemaumau and passive spillage of the lava over spatter rims when the lake was at capacity. He carefully notes the distribution of flank discharges, some of which his party traversed en route to Kilauea summit, and summarizes the accounts of flank eruptions by others both before and after his own visit. He deduces that the low slopes of the typical Hawaiian domed volcano result simply from flank eruptions keeping pace with summit eruption, so that the edifice does not steepen as it grows until, perhaps, toward the end of its activity, when flank eruptions cannot be sustained. He speculates on the nature and necessity of dikes to feed flank eruptions. He calculates that, at eruptive rates he was able to estimate from his own and others observations, it would take approximately 400,000 yrs to construct Mauna Loa above sealevel, a figure not greatly different from modern estimates.

Dana notes the presence of lava cones up to a mile in diameter with side slopes up to 15° on the floor of Kilauea crater and on its flank, then distinguishes these from cinder and tuff cones. In his summary he says that lava cones begin and progress as cones and are exact models of the great mountain volcanoes. This is thus evidence against von Buch's elevation craters. Lava cones are

> *better evidence on this point than any supposed impossibility of lavas descending rapid slopes; for we have shown that the conical form commences through eruptions from the terminal vent and fissures, and undergoes no essential change, as enlargement goes on. We see no foundation whatever in the Pacific for the view that the mountains waited till the material was thrown out before the action began which elevated the centre. . . . While, therefore, we present no opinion here as to the particular cases claimed as instances of elevation craters, we cannot admit the hypothesis to the rank of a general theory* (1849, p. 370).

In a long footnote, however, Dana goes on to note similarities between the geology of the Canary and Hawaiian Islands, pointing out specific difficulties in the Canaries for the hypothesis of elevation craters.

Dana makes the point that the interiors of large volcanoes should have masses of coarsely crystalline material, corresponding to the subterranean levels of the conduit systems which supply lavas to summit calderas. There is no reason to suppose that these have arisen, piston-like, into the heart of an elevation crater. He points to "feldspathic" rocks, such as amphibole gabbros and syenites, which he sampled as clasts in alluvium at the mouth of the Papenoo on Tahiti, and similar rocks at La Palma in the Canaries, as evidence that such massive rocks are exposed in the interior of volcanic islands. He considers that such coarse-grained rocks have to crystallize from conduits beneath summit craters but points out that, in proportion to the breadth of Hawaiian volcanoes, the two conduits beneath Mauna Loa and Kilauea must be completely separate to very great depth. Since the two do not erupt with any kind of regular synchroneity, their eruptive mechanisms cannot be linked. He took this to mean that the immediate causes of eruption were actually quite shallow and saw that this might have to do with the interaction between ground water and magma. Aspects of this view were carried forward with Daly's (1933) two-phase convection and Jaggar's (1947) conviction, after 26 yrs of observation at Kilauea, that "volcanic action is alternately magmatic and phreatic."

Besides Hawaii, the only comparably youthful volcanic landscapes Dana saw elsewhere in the Pacific were on the islands of Upolu and Savai'i at Samoa. However, whereas on the island of Hawaii the volcanic centers are far apart and each coincides with a substantial summit, on Upolu the vents are crowded together, sometimes even nested, and arranged along the long axis of the island, extending to tufa cones offshore, which Dana carefully describes. Upolu also has a deeply embayed and rugged northeastern coast, centered on Fagaloa Bay, and Dana actually considers that this might represent a substantially older volcanic construction. Nevertheless, in the end he chooses to suppose merely that volcanic activity was substantially uninterrupted, and that on this one island as well as along the chain itself, volcanism progressed from east to west, opposite to the trend in the Hawaiian and Society groups.

The geology of Upolu, in particular the contrast in age between lavas of the Fagaloa volcanic series on the rugged northeastern coast and those emitted from the youthful vents was the eventual key to resolving the Samoan age progression. First, a distinction between shield and post-erosional volcanism at opposite ends of the chain had to be documented and understood (Stearns, 1944; Kear and Wood, 1959). Then the age progression of both emergent and submerged shield portions of the chain established by comparative geomorphology and relationship to offshore reefs would show a proper Hawaiian-type of age progression, with the youngest *shield volcanoes* to the east (Natland, 1980). Savai'i and Upolu in Western Samoa are simply older shield volcanoes much more deeply buried by rejuvenescent or post-erosional volcanism than Hawaiian shield volcanoes of similar age, to the extent that Savai'i looks like a young island. The Fagaloa volcanic series of Upolu, however, is not so deeply buried and represents a shield volcano active between 3.0 and 1.4 Ma (Natland and Turner, 1985 and unpublished data). Even older shield volcanoes underlie shallow submerged atolls to the west, out to Combe Bank, dated at 14 Ma (Duncan, 1985). A single major post-erosional rift zone transects the axes of Savai'i and Upolu, may reach Tutuila, and could be a consequence of stresses imparted by deformation of the underlying Pacific plate at the northern end of the Tonga Trench (Natland, 1980).

Samoa, especially Upolu, provided two misleading bits of information to Dana. First, he did not have enough geomorphological information to understand the age progression there. Second, Upolu showed that certain volcanic islands may form along long, linear rift systems, and this along with the arrangement of Pacific volcanic chains along linear or slightly curving trends contributed to Dana's persuasion that the high, subaerial volcanoes simply cap elongate ridges, of which the modern ones are parallel in the Pacific. In consideration of age progressions, then, he supposed that entire linear segments (for example, the Loa or Kea trends of the Hawaiian group, and conceivably the entire Hawaiian chain out to Midway and Kure) originally were active simultaneously along their entire lengths, but that volcanic action most eventually focuses into volcanic centers, with these dying out–"the fires soonest extinct"–in one direction or another. Dana's shipboard colleague Couthouy posed in correspondence the alternative that each volcanic center in a group like the Hawaiian chain actually rises independently and successively in the order suggested by the age progression from the deep sea bed, and that none of them cap an actual ridge once active along its entire length. But in the absence of sufficient offshore physiographic data, and with Samoa providing an actual subaerial counterexample, Dana could only demur.

Better evidence for Dana's fissure hypothesis exists on the floor of the Pacific. A series of elongate volcanic ridges (called Puka Puka ridges) have been discovered and surveyed near the East Pacific Rise in the western Pacific (Winterer and Sandwell, 1987; Lynch, 1994). Although many of these ridges are capped with alkalic basalts and related differentiated lavas, similar to late-stage rocks on Hawaiian volcanoes (McDougall and others, 1994), they do not show a Hawaiian type of age progression (Sandwell and others, 1994). Instead, they appear to have formed along fractures created by a regional tensional stress regime, orthogonal to the direction of spreading, imparted to the rigid lithosphere by rotating cells of convecting asthenosphere. This is virtually the same mechanism that Dana suggested nearly 150 yrs ago.

DANA'S PACIFIC SYNTHESIS

Dana's summary chapter presents a synopsis of all the linear and curving trends he could discern from charts in the Pacific. He identified linear chains; for example, Hawaii, Samoa, the Societies, the Tuamotus, the Marshalls, and the Marquesas, with their segmented and parallel sub-trends. He also identified curving chains; for example, the Aleutians, the Kuriles, and the Ladrones or Marianas. In the latter, the curvature is especially evident when the non-volcanic islands of Yap and Palau are included. The linear chains occupy the interior of the Pacific and have the most obvious age progressions, which Dana indicated by reef category (none, fringing, barrier, atoll), whereas the curving chains are concentrated along the perimeter. The age progressions of the linear chains and their concurrent subsidences Dana deduced to belong primarily to the Tertiary epoch. The linear chains are also overwhelmingly basaltic in composition and thus contrast with continental crust in general. Their volcanoes differ in form, as well as composition, from the steep-sided, explosively erupting volcanoes of the curving chains.

Dana, like Darwin (1842) before him, undertook a regional evaluation of the patterns of elevation and subsidence of reefs in the Pacific, finding regions of uplift around Australia and in Melanesia and subsidence in Polynesia. His most striking extrapolation was the pattern of regional subsidence in the western Pacific which he deduced from the varieties of reefs on the linear island chains and the evidence they provided for age progressions. Dana came to the conclusion that there must be a vast tract of the western Pacific where deeply submerged drowned atolls crown ancient and extinct volcanoes.

He proposed that there is a principal axis to this region of greatest subsidence between the reef-bearing islands of the Hawaiian and Marshall chains and trending to the northwest. This axis extends from just east of the Tuamotus to a point about halfway between Midway Island in the Hawaiian chain and Japan. Dana later noted, *". . . that this axial line, or line of greatest depression, coincides in direction with the mean trend of the great ranges of islands, it having the course N. 56°W"* (1890, p. 363). He provided the available information on soundings which showed a maximum of 3448 fathoms (6306 m) to the bed of the Pacific along this line near the Phoenix group of atolls. He speculated that, where there are whole tracts of nothing but atolls, subsidences had to amount to an average of at least 9000 ft (2743 m), the average height above sea level of a young volcano in this part of the Pacific. He noted the generally diminishing size of atolls to the west and northwest in this region, and suggested that this is related to the extent of subsidence. He hypothesized that still further along this trend toward Japan, where there are no atolls, there would nevertheless be extinct and deeply submerged atolls, representing an even greater subsidence. Recalling this conjecture late in his career, he wrote, *"A range of deep-sea cones, or sunken volcanic islands, would be as interesting a discovery as a deep-sea sponge or coral, even if it should refuse, excepting perhaps a mere fragment, to come to the surface in the dredge"* (1890, p. 410).

The province of drowned, erosionally truncated, and reef-encrusted volcanoes was duly discovered by the executive officer of a sonar-equipped U.S. naval vessel during World War II, Harry Hess (1946), who termed the flat-topped mountains guyots, in honor of Arnold Guyot, after whom the flat-topped building which housed Hess's geology department at Princeton was named. Guyot was also a colleague and correspondent of Dana's and the namesake of one of his children. Dana no doubt would have been astonished at the number of these features. There are literally hundreds of them precisely where he predicted. The mountain ranges are familiar to us now–the Mid-Pacific Mountains, the Wake and Magellan seamounts, the Japanese guyots. Dredging revealed them systematically to be drowned Cretaceous rudist-bearing reefs and carbonate platforms (Hamilton, 1956; Heezen and others, 1973). Once enough was known about them, Menard (1958, 1964) used the acoustically charted depths of guyot summits to delineate the crest of what he called the Darwin Rise. This, he surmised, was an extinct, subsided, equivalent of the East Pacific Rise, which at that time was not realized to be a spreading ridge. The depths to the guyot summits indicated the extent of their subsidence. The pattern of subsidence Menard

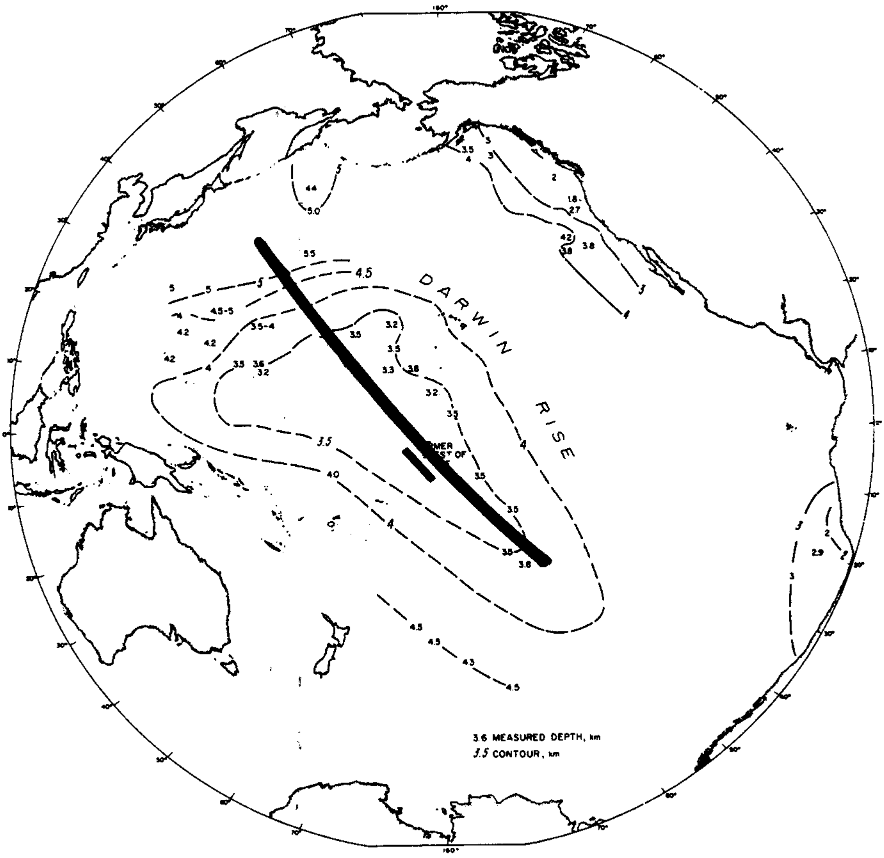

Fig. 1. Dana's line on the Darwin Rise; figure modified from Menard (1964). Contours give the original depths to the sea floor, based on present-day depths less depths to the summits of guyots. The short, thick, line is where Menard placed the former crest of the Darwin Rise.

deduced, based almost precisely on the submarine equivalent of the evidence from islands and atolls that Dana applied to the same end, was nevertheless exactly the opposite of Dana's. The flanks of the Darwin Rise had subsided the most; the summit the least. Nevertheless, the crest of Menard's Darwin Rise corresponds almost exactly to Dana's axis of maximum subsidence in the western Pacific (fig. 1), although apparently Menard never realized this, since he does not cite Dana in this connection in either his earlier writing nor his final publication on the topic (Menard, 1986).

Modern surveying shows that these drowned ancient islands include both fully developed carbonate banks with atoll-like rims enclosing thickly bedded lagoonal sediments, truncated volcanoes with apparent barrier reefs enclosing volcanic stubs, and even some beveled volcanic summits without reefs (fig. 2; Winterer and others, 1993). The region of the Pacific where these volcanoes lie is now known to be the most ancient (Jurassic) and deeply subsided portion of the Pacific plate, having regional seafloor depths of between 5 and 6 km. One guyot off Japan is among the oldest dated, at 118 Ma (Pringle and Duncan, 1996).

Several guyots were drilled during Ocean Drilling Program Legs 143 and 144 (Sager, Winterer, Firth and others, 1993; Premoli-Silva, Haggerty, Rack, and others, 1993). Once coring reached beneath younger pelagic sediment caps, it systematically recovered very shallow-water lagoonal sediments all the way down to subaerial basalts. Total subsidences of the volcanic summits below sealevel range from 1200 m in the Marshall group to nearly 3000 m at older features in the Mid-Pacific Mountains. If, as Dana postulated, the average summit height of the volcanoes at the peak of their growth was about 2700 m, then total subsidences were on the order of 4000 m in the Marshalls to nearly 6000 m in the Mid-Pacific Mountains. In all respects, Dana's speculations have been confirmed.

DANA'S THEORY OF THE EARTH

In Chapter VII of his report, Dana summarized his global perspective. He wrote:

> *The truth forces itself upon the mind, in view of these facts, that some universal cause has operated in producing results so general, and so mutually dependent–a cause, through which, the very framework of the globe has received its characteristic features* (1849, p. 426).

He then advanced his universal cause. Elements of it were inspired by simple observations of cooling lava. Our planet is a molten, or partially molten, ball that is cooling and shrinking. One portion of the globe consists of elevated fold belts; the other of volcanoes rising from a great abyss. The continents represent the coldest and most contracted (folded and wrinkled, Dana noted, like pahoehoe) portion of the shrinking surface of the planet; the ocean basins represent the warmest, most volcanically active, and least contracted portion of the planetary surface. The old continents are elevated because they crystallized when the earth was larger; contraction of the global spheroid beneath the relatively rigid continents led to the compressional dynamics of fold belts, thus an increase in the thickness of the continents. The transition zones, where stresses are most concentrated (where wrinkling and large crustal displacements are now taking place, like the pressure ridges on lava lakes), are the great volcanic arcs and associated seismic zones of the globe. Unequal subsidence and variations in volcanic activity at different times are related to changes in sealevel, a view that is still current (Larson, 1991).

Within the central Pacific, the parallel ridges and broad zones of regional subsidence correspond to a dual fracture system, northwest-by-west and northeast-by-north, representing the orthogonal orientation of simple dilational forces, resulting from contraction (in the manner of orthogonal fractures in massive dikes) that promotes development of fissure systems in the crust. Dana cited others who had also noted such patterns. Volcanic ridges

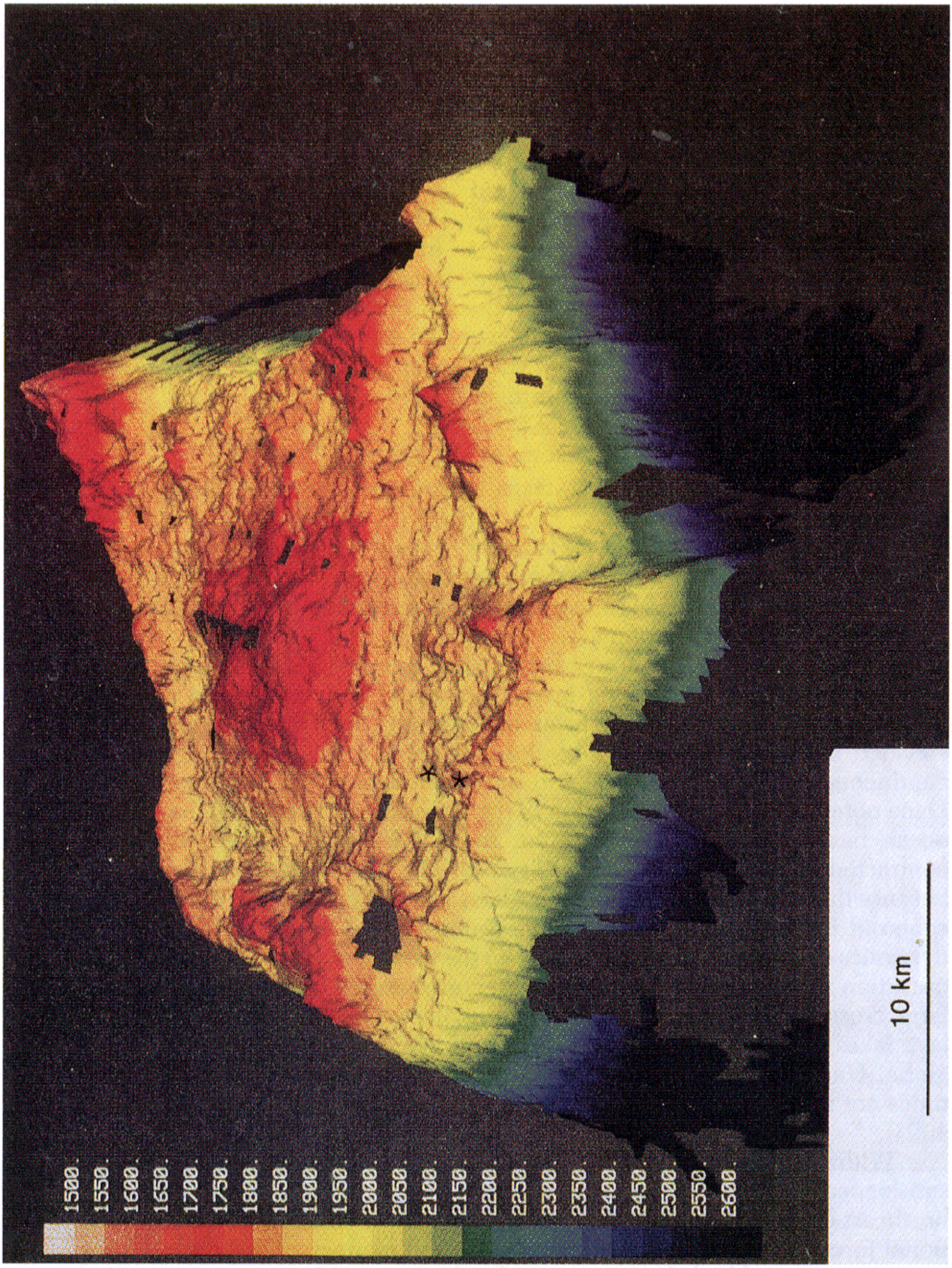

Fig. 2. Shaded relief image of the summit area of Charlie Johnson Guyot, western Pacific (31°59'N, 148°15'E), constructed from high-resolution SeaBeam swath mapping (Winterer and others, 1993). The shallowest point on the summit is 1460 m below sealevel.

represent fractures over hotter regions of the Earth, pulled apart by contraction in the swales on either side. Subsidence is a continuation of this process in the vertical direction but is most pronounced where the crust is thin that is, in the ocean basins rather than the continents, because it is hotter there to begin with. The Pacific volcanic ridges occur within "large circular or elliptical areas that continued open as centres of fluidity and eruptive action." They coincide with a "boiling movement or circulation (up at centre and down around the sides)," or a "vast circulatory or cyclosis movement" beneath the ridges. In modern terms, this is convection. Dana thought that this is caused by "escaping vapours," by which he did not mean the recycled groundwater to which he attributed most eruptive phenomena. Instead, without the benefits of laboratory experiments or thermodynamic rigor, he was appealing to the causes of eruptions thought most likely in his day, in particular the effect of fluxion, or exothermic reactions between fluids and solids, advocated by Davy (Siegfried and Dobbs, 1968) and most other students of volcanic action. Hawaii showed to Dana that these processes had to occur at great depths within the Earth.

One can see in this the germs of several modern ideas: first, that mid-plate volcanoes are manifestations of convective circulation; second, that the eruptive products of mid-plate volcanoes are intrinsically enriched in volatiles, nowadays viewed as one aspect of source heterogeneity, particularly enrichment in incompatible elements; third, that the action of volatiles is conducive to partial melting since, as we now would describe it, the mantle solidus is depressed by the presence of water. The general contrast between the hotter, volcanically busy ocean basins and the colder, contracting or inactive continents also has a modern feel to it. But the differences between the continents and the ocean basins are so well known to us now that it is hard to imagine a time when they needed to be demonstrated. To dispel a widespread misconception, for example, Dana was compelled to write:

> *We should beware of hastening to the conclusion that a continent once occupied the place of the ocean, or a large part of it, which is without proof. To establish the former existence of a Pacific continent is an easy matter for the fancy; but Geology knows nothing of it, nor even of its probability* (1849, p 400).

On the broad scale, Dana's theory at once neatly provided a general explanation for contrasting elevations of continents and ocean basins, the occurrence and distribution of linear and arcuate volcanic chains, and the origin of fold mountain belts. It linked everything to one simple unidirectional process, that of global contraction. It had sufficient latitude to accommodate large lateral displacements of blocks of crust along transcurrent faults. It offered a ready explanation for continental growth, and, within Dana's lifetime, geological mapping proceeded to the point where he could use the concentric pattern of successively younger orogenic belts in North America in support of his hypothesis. The Earth really has a history–it is not Lyell's unending repetition of the same geological processes–and one could even imagine that there was a beginning.

> *According to this view, the general forms of continents, and those of the intermediate oceanic depressions, however modified afterward, were to a great extent fixed in the earliest periods of the condition and nature of the earth's crust. They have had their laws of growth, involving consequent features, as much as organic structures* (1849, p. 436).

Here, fully announced, in the parting sentence of his summary chapter, were the doctrines of the permanence of continents and ocean basins and the historicity of the Earth.

This has to be one of the defining moments in the intellectual history of the Earth Sciences. But note this: Although the stability of continents and ocean basins became one of the intellectual pillars of North American geology and stabilist interpretations of orogeny, most of Dana's own work in Precambrian and Appalachian geology was still ahead of him. The sources of this first pronouncement were in observations of Pacific volcanoes, islands, and reefs. Dana's summary emphasizes processes that are grand extrapolations of the volcanic phenomena he set down so vividly in his report. The language and imagery of his contractive model for the Earth are drawn from volcanology. Also note that, although Dana stated an opinion he intended to support, he still qualified it. He was cautious. Phrases such as "... the general forms", "... however modified afterward", "... to a great extent" all indicate his awareness of the great gulf of ignorance that had to be spanned if the theory was to become more firmly established. Here he was announcing the programme for his life's work.

One can only speculate whether some spark of information or insight might have keyed Dana into the concept that the continents and ocean basins can move around. Slags move around on the tops of molten iron, pots of heating soup, and lava lakes. Firm and consistent age progressions for three or four island chains, not just the Hawaiian and Society groups, with no contradiction at Samoa, might have pointed Dana in the direction of propagating fractures atop moving convective cells, or even motion of the Pacific floor over convective cells. But this did not happen. Dana became committed to formation of long fractures and wholesale building of volcanic ridges along them, with the fires only burning out in one direction or another. This anchored the ocean basins and, thus, the continents, in their places.

After Dana, Pacific regional geology languished for nearly a hundred years. Some individual islands were carefully described, and a great deal of work was done in the Hawaiian Islands. But a broader perspective on the Pacific could not be achieved until sonar began to be used to chart the seafloor after the Second World War. The Geology report for the Exploring Expedition, issued in only a few hundred copies, found few readers. Its synthesis was little known and may not even have been of much use to the handful of geologists who continued to study individual Pacific islands or island groups. Lawrence Chubb, for example, who described Pacific island groups over a period of 30 yrs, does not even cite Dana in his summary of the age progressions and petrological characteristics of those chains (Chubb, 1957), even though the progressions were based on almost exactly the same evidence Dana used (erosional degradation and reefs). Although Dana's later writing drew heavily on the report, the summaries of Pacific regional geology he presented were usually only a portion of something otherwise devoted to specialists (for example, *Corals and Coral Islands,* in 1890). No one else attempted a regional synthesis until Menard (1964), after the seafloor in the Pacific had been sensibly charted.

The stability of continents and ocean basins, however, became a firmly grounded article of faith for several generations of North American geologists. Its persistence was felt even to the advent of seafloor spreading. Until then, most geologists surmised that at least some portions of the ocean basins had to be very old. Hess (1946), for example, thought that the guyots uncovered by the Navy's sonar equipment were probably Precambrian in age. Dana did not speculate on the ages of the drowned atolls he predicted, but he probably would not have expected them to be that old, since he considered that chains formed completely of atolls are Tertiary or younger. Drowned atolls with twice the total subsidence of an island atoll might be twice as old. Nevertheless, the great age of ocean basins was a common presumption. Willard Bascom (1959), in an article for *Scientific American* on the Mohole Project, suggested that one reason a hole to the mantle should be drilled in the ocean basins is that a complete stratigraphic record might exist at single locations in the ocean basins reaching back to the earliest days of Earth history, to "Cosmic Time"–prior even to the Archean. The laterally accreted continents, in comparison, have an incomplete record and certainly not one that can be reconstructed at a single location.

Taking Dana's hypothesis literally, however, continuous stratigraphic records through all Earth history should be available at almost any location in the deep. Or so Bascom thought. The report on Geology does not consider this possibility, and perhaps it would have proven a difficulty to Dana. But Dana's most far-reaching geological conclusion, based on his wanderings in the Pacific, that the ocean basins have always been there, was in the hearts and minds of geologists several generations hence, before the revolution swept it away.

ENVOI

I have tried to trace the development of Dana's perspective on global geological problems from the time when he first began to think about them, during the U.S. Exploring Expedition of 1838-1842. Dana's bibliography runs to more than 240 articles and books, and of these only about 10 percent are devoted strictly to volcanoes and volcanic islands. Most of these were written toward the beginning and at the end of his long career. One can get the impression that other concerns practically pushed these ideas from his mind for long periods of time. Even in his popular geology text, *The Geological Story* (1895), the very last book he ever wrote, there is only a single page devoted to Making of Mountains and Attendant Effects by Igneous Ejections and only the briefest description of coral reefs and atolls. But in fact his interest in the issues first raised on the Exploring Expedition never waned, and his return to these topics late in life underscores their importance to him. At age 74, and in considerably more comfort than during the Exploring Expedition, he once again visited the Hawaiian volcanoes and summarized his results and years of collecting of volcanological reports in a new book (Dana, 1890). Hoffmeister (1940) describes this text as the essential antecedent of Jaggar's long tenure, beginning in 1912, of careful observation and experimentation at what became the Hawaiian Volcano Observatory; Jaggar (1947) acknowledged this. Yet after the Exploring Expedition, most of Dana's career was devoted to studies of continental geology, in which he followed out the logical consequences of deductions that were so grounded in his youthful study of volcanoes and volcanic islands.

Dana was the first geologist to perceive the broad geographical relationship between volcanic phenomena, previously attributed to local causes, and the scope of forces acting within the Earth. In his attention to the distribution of forces in and around the Pacific basin, he provided the first conjectures on actual spatial relationships between the planet's interior and the continents, fold belts, volcanic arcs, and ocean basins on its surface. He postulated what are essentially convective phenomena (his circulatory or cyclosis movements) as the mechanism which focuses heat beneath volcanic chains. He had no concept of the contrast between mantle and crust in the ocean basins. Nonetheless, in appealing to "internal fires within the globe" as the link between volcanic centers in volcanic groups, with those groups characterizing a major portion of the globe, he promoted a conception of volcanism that was planetary, not merely surficial, in scope. His search for physical causes and appropriate comparisons led him even beyond the Earth. Before he finished the Report, but while his thoughts were still on the Pacific, he speculated on comparisons between the diameters of terrestrial and lunar craters and compared the low angles of lava flows on Mauna Loa and Kilauea with those filling the lunar maria (Dana, 1846).

Dana's Christian sensibility pervades much of his writing. However, although there is often reference to Divine Plan, once he stumbled onto the possibility that there is a "grand cause" which can be read from what he called the "physiognomic pecularities" of the globe, he clearly got on with trying to describe in physical terms what actually happened. In most of his work, whatever ideological axe he may have had to grind was generally obscured by the wealth of information and the cogent thinking he provided. Dana's good fortune as a young man was to have been allowed a long opportunity to contemplate his science in the context of an extraordinary field experience, global in its scope. He pursued the ideas thus formulated and sustained his planetary perspective, throughout a long life in science. The Exploring Expedition gave him the encompassing view of the earthly cathedral to do so. That the cathedral existed and was constructed for the delight and instruction of human intelligence, he never doubted. At the end of his final and most influential text, he provided a summary and justification of his own vast scientific effort.

> *Whatever the results of further search, we may feel assured, in accord with Wallace, who shares with Darwin in the authorship of the theory of Natural Selection, that the intervention of a power above Nature was at the basis of Man's development. Believing that Nature exists through the will and ever-acting power of the Divine Being, and that all its great truths, its beauties, its harmonies, are manifestations of His wisdom in power, or, in the words nearly of Wallace, that the whole Universe is not merely*

> *dependent on, but actually is, the Will of one Supreme Intelligence, Nature, with Man as its culminant species, is no longer a mystery* (1896, p. 1036).

Dana also dedicated himself to writing nuts-and-bolts manuals for the training of geologists and the education of the interested public. This was in accord with his attitudes about citizenship and Christian duty, and it also supplied him income. Geology was, indeed, a growth industry in the years after the Civil War. As a scientist, Dana became the quintessential academic, training younger geologists and expressing his views with extraordinary persistence in books, manuals, and the journal literature.

Dana was the first of a series of distinguished American geologists who worked in the Pacific. His thought and influence can be traced through the writings of W.M. Davis and R.A. Daly regarding coral reefs, the Pleistocene, and sealevel, to T.A. Jagger, Harold Stearns, and Gordon Macdonald concerning Pacific volcanoes, to scientists who were able to take advantage of the tools of modern marine geology including Harry Hess, E. Dale Jackson, S.O. Schlanger, and H.W. Menard. These scientists were as diverse in their approaches to the Dana legacy of problems as it is possible to be, and some of them did not know how much they owed him. Dana thus carved an unusually wide and deeply pervasive professional niche. To someone who takes up his concerns and cares to be at all a scholar, J.D. Dana ultimately is impossible to avoid and essential to acknowledge.

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