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JAMES DWIGHT DANA'S OLD TECTONICS– GLOBAL CONTRACTION UNDER DIVINE DIRECTION

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ABSTRACT. The old global tectonics of James Dwight Dana was one of America's first major contributions to theoretical geology. That theory began with Dana's experiences in the Pacific on the Wilkes Exploring Expedition (1838-1842), which paralleled closely the experiences of Charles Darwin a few years earlier. He refined Darwin's hypothesis of oceanic subsidence in 1843 by adding geomorphic evidence of subsidence, differential crustal responses, and variable island ages, and went on to develop a comprehensive global theory during the remainder of his life. Dana accepted the long-standing assumption that the Earth began molten and had contracted as it cooled. Early in his career, he recognized the fundamental geologic difference between continents and ocean basins, which he believed had arisen early in the history of the planet. He inferred that the northwest and northeast trends of many linear island chains, shorelines, and mountain ranges reflected fundamental *cleavage lines,* which he thought had originated during Archean thermal contraction and continued to influence subsequent evolution of the crust. Because continents "were first free from eruptive fires," they must have cooled first and, being very old, must also be permanent. With their active volcanoes and depressed topography, ocean basins must be the chief loci of cooling and contraction. Furthermore, their greater subsidence inevitably causes lateral pressure, folding, and uplift of continental margins to form mountains.

The *geosyncline* was a late refinement from 1873 in response to Hall's 1857–1859 "theory of mountains with the mountains left out" (according to Dana). Contractive pressure buckled the continental margin; a downbuckle or *geosynclinal* received thick sediment derived by erosion of a complementary upbuckle or *geanticlinal.* Finally, the whole system failed and became stabilized as an addition to the growing continent while a new geosyncline-geanticline couplet formed oceanward. Dana regarded North America as the perfect, simple example of continental evolution, which "revealed God's plan of creation" better than any other continent, therefore it could instruct the rest of the world. Its margins reflect the northwest and northeast cleavage lines with the oldest Azoic rocks representing the "first germinant spot" or nucleus around which the continent had expanded by additions of mountain belts through successive "vibrations of the crust." Thus was born the important concept of *continental accession or accretion* with "contraction as the power, under Divine direction, for humanizing the earth." Dana's old global tectonics had profound influence even after thermal contraction lost favor around 1910. First Chamberlin's gravitational contraction and later thermal convection extended that influence and helped nurture the American resistance to continental drift until the new tectonics appeared in the 1960s.

INTRODUCTION

James Dwight Dana's theory of global tectonics developed over a half-century was a powerful paradigm, which greatly influenced the development of American geology right up to the advent of the New Global Tectonics in the 1960s. The appeal of this first American global theory was the relatively simple mechanism of contraction of a cooling Earth to explain in a unified way the large-scale architecture of continents versus ocean basins, the locus of volcanoes, and the origin of mountains. Dana showed a bit of nationalism in declaring that North America now had its own geology and was the perfect model continent, being geologically simpler than others. He piously declared further that, because the Deity had provided perfection here, America was preordained to instruct the decadent old world. It was as if Dana had appointed himself as Pope to spread the geological good news, which he did for more than three decades through a series of 17 papers published in the *American Journal of Science* from 1843 to 1890 as well as many summaries of his theory in other papers and in four editions of his *Manual of Geology* (published 1862, 1874, 1880, 1895), *Textbook of Geology* (published 1864), and *The Geological Story Briefly Told* (published 1875, 1895). In reality the publications on tectonics are of greater significance to the history of geology and were of greater interest to Dana himself than his mineralogy or his many other contributions with the possible exception of those on coral reefs and volcanic islands.

Dana was born in 1813 into a puritanical merchant's family in Utica, New York. Religion was taken very seriously; the scriptures were seen as the literal word of God, and it was one's first duty to serve God (Gilman, 1899). James Dwight never deviated from his childhood indoctrination in these precepts, and he translated his pursuit of science through research and teaching as his way of working in the service of God. This fervent dedication conditioned Dana's world view in which science can "aim to decipher some new words in the volume of Nature, that we may learn the will of Him who has ordered all things well, and comprehend more fully His laws in the government of the universe." (Dana, 1856a, p. 1). His "religious faith ... sanctified all the work and all the experiences of life" according to a former student, William N. Rice (Rice, 1914, p. 39-40). But why did Dana's several contemporary geologist memorialists not mention this fundamental aspect of his character (Beecher, 1896; E. S. Dana, 1895; LeConte, 1895; Williams, 1895)? Did they share his view enough to take it for granted, were they embarrassed by it, or had the tension between religion and science ceased to be an issue by the time of his death? It was certainly still very important to Dana, as evidenced by strong providential overtones carried into the last edition of his *Manual of Geology* (Dana, 1895, p. 1036).

Coupled with his life-long religious dedication was an "irrepressible instinct for generalization" (Rice, 1914, p. 9 and 38), which motivated Dana in a manner similar to James Hutton a century earlier, namely to formulate an inclusive, teleological scientific theory to explain the preparation of the world for humankind. "Dana linked the tiniest coral polyps to the grand movements of the earth's crust" (Stanton, 1981, p. 552), but his penchant for synthesis sometimes led him to confuse analogy with identity, to commit over-generalization, and even to reveal wishful thinking (Prendergast, 1978, p. 239-243; Rice, 1914, p. 38). Perhaps this tendency was reinforced by a pious certainty about the justness of his calling. In any case, throughout his entire professional career, Dana would return again and again to refine and extend his theory for the evolution of the globe "under divine direction . . . [to fit] it for a new age–the Age of Mind." (Dana, 1856b, p. 349). Because he was America's single most prolific geological writer, outdoing even James Hall, his theory was bound to become widely known.

Immediately after his studies at Yale College, young Dana took a position in 1833 as instructor to midshipmen on a U.S. navel vessel cruising in the Mediterranean for fifteen months. During this voyage, he visited Mt. Vesuvius, which was building to an eruption in 1834. His first publication was a paper in the *American Journal of Science* for 1835 about that volcano. Thus Dana's career began in a tectonically active foreign region. Two years later, while working for Benjamin Silliman at Yale, he published the first edition of *A System of Mineralogy.* He then was recommended by Asa Gray of Harvard to join the United States Exploring Expedition of 1838–1842 under the command of Lieutenant Charles Wilkes (Stanton, 1981; Appleman, 1985). Although he signed on as geologist, the discharge of conchologist Joseph Couthoy midway in the expedition resulted in Dana's doubling as zoologist. Thenceforth, Dana shared the collecting of animal specimens with artist Joseph Drayton and, after the cruise, was responsible for writing reports on Zoophytes (or Coelenterata, published 1846) and Crustacea (published 1852-53), as well as geology (published 1849), while Augustus Gould wrote on the Mollusca. Dana soon became almost as well known for his writings on corals as for his geology. Thus, like Darwin only a few years before, Dana was to derive both important geological and biological insights from the Pacific, which would provide much of the foundation for his career. In 1853 Dana published his book, *On Corals and Islands;* a revised version appeared in 1872. Still later, he published the book *Characteristics of Volcanoes* (Dana, 1890d).

The present paper is a sequel to my earlier contributions about Dana's geosynclinal theory for mountains (Dott, 1974, 1978, 1979). In this paper, I have emphasized the development of his thinking prior to the formulation of the geosynclinal concept in 1873. I have also included more of Dana's own fascinating rhetoric, which reveals much about his personality and modes of thought. The result is a more complete treatment of the overall global theory, which seems to me to have been the pre-eminent geological preoccupation of Dana's long and exceptionally productive career.

THE WILKES EXPLORING EXPEDITION AND OCEANIC SUBSIDENCE

For both Dana and Darwin, the most important geological insights from their respective expeditions were gained from the Pacific and its margins. Wilkes left his scientists in Australia in 1839 while he explored the margin of Antarctica. During this interlude, Dana learned of Darwin's theory of subsidence of the Pacific basin to explain the differences among its volcanic islands and associated coral reefs (Stoddart, 1994). Dana had by then seen many of the reefs and islands for himself, and Darwin's explanation provided an immediate "flood of light." Moreover, his studies of Fiji, Tahiti, Hawaii, and other islands allowed Dana to add to Darwin's observations and to begin the formulation of his own, more broadly encompassing theory of global geology. Dana refined Darwin's Pacific subsidence theory in several ways. From the distribution of reef types within the Pacific, he defined a line of greatest subsidence trending west-northwest between the Hawaiian and Marshall Islands, and he delineated regions of differential subsidence reflected by dominances of fringing reefs versus atolls and even some areas of uplift (fig. 1). He also recognized that the Hawaiian and several other island chains were older toward the northwest. At Tahiti, he provided important new evidence of crustal subsidence by recognizing that the deep dissection of the central volcano and marine embayments around the island's perimeter indicate fluvial erosion followed by partial drowning of valleys due to subsidence (Appleman, 1985; Stoddart, 1994); Darwin had incorrectly ascribed these embayments to erosion by marine currents. While in Australia, Dana also concluded correctly that the great gorges of the Blue Mountains west of Sydney had been carved by the streams that now flow in them rather than by marine currents and waves as Darwin had argued. Dana and Couthoy established the geographic limits of Pacific coral reefs and demonstrated for the first time that their distribution was controlled by water temperature. After the Expedition, an unfortunate rift developed between them over priority for the recognition of temperature control.

In the last lines of his first paper about Pacific subsidence, Dana noted that the western margins of both American continents had been elevated as the Pacific had subsided, a reciprocity hinted at by Darwin (Dana, 1843). Although Dana did not specify a cause-and-effect relationship, later papers indicate that he wanted it to be so. Together with the implications of very large-scale subsidence of much of the Pacific basin, Dana demonstrated that oceanic crust was composed of only two rock types, basalt and coralline limestone, in contrast with the greater heterogeneity of continental crust. In the Pacific he also first developed his concept of *fundamental cleavage lines* or structural lines in the crust, which he deemed were established very early and persisted throughout history as major, controlling structural trends. He reckoned there were two fundamental trends, northwesterly (Hawaiian Islands, Tuamotu Archipelago, Solomon Islands, New Guinea, et cetera) and northeasterly (New Zealand, Kermadoc Islands, and the eastern edge of Australia). He saw these trends repeated in the western and eastern margins of North America (fig. 1). Dana's emphasis upon fundamental trends suggests an influence by *loxodromism* then popular among some European geologists, most notably Élie de Beaumont, who carried the geometric analysis of such patterns to an extreme (see Greene, 1982, p. 112-121).

GLOBAL CONTRACTION BY COOLING AND THE ORIGIN OF CONTINENTS

Unfortunately, Congress did not support the publication of the results of the Exploring Expedition as well as it had the expedition itself. Only 100 copies of Dana's geological report were funded, but he personally paid for an

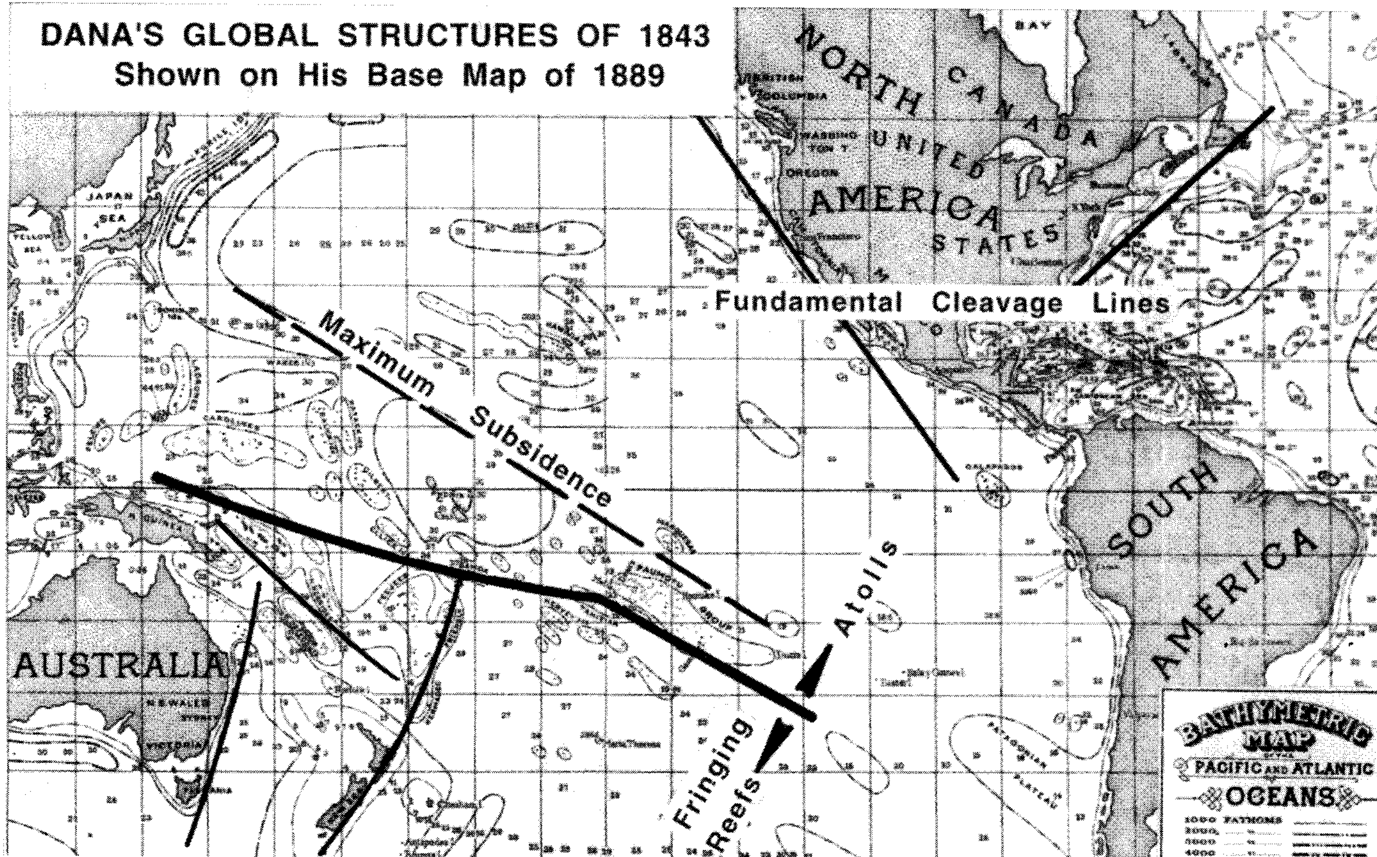


Fig. 1. Structural features noted by Dana in 1843 plotted here on his bathymetric map of 1889 (slightly cropped for greater clarity in publication). All of the features highlighted were recognized by Dana during the U.S. Exploring Expedition (1838-42); a similar map was published in volume 10 (*Geology*) of the expedition reports, which was reproduced in Appleman, 1985 (p. 94).

additional 100. Fortunately, he published promptly in other media the ideas nurtured on the expedition. The first, on Pacific subsidence appeared in 1843, the essentials of which have just been summarized. A hint of his global theory was sketched in an 1846 paper entitled "On the Volcanoes of the Moon," and then a flood of four papers in 1847 spelled out the theory in more detail. Papers of 1856 and 1866 were little more than restatements with a few refinements. These seven papers are summarized in this section. The styles of these is interesting, for most are little more than extended abstracts and several are simply outlines and lists. In 1846, coinciding with the beginning of his flood of global papers, Dana had assumed the co-editorship of the *American Journal of Science and Arts* with his father-in-law, Benjamin Silliman. The insertion of so many short contributions may indicate a free use of editorial privilege for publishing his stream of conciousness, or alternatively some of these may have been written as last-minute fillers before press time.

Dana's Pacific experiences qualified him as a pioneer volcanologist as well as marine biologist. He made the first detailed observations of several Pacific volcanoes, such as Tahiti, Fiji, and especially Kilauea and Mauna Loa; he also had visited Madeira, Cape Verde, and some volcanoes in Oregon and California during the Expedition (Appleman, 1985). From all this, Dana was the first to recognize the important difference between relatively mild eruptions characteristic of oceanic shield volcanoes and more explosive Vesuvian ones. He was also able to marshall evidence that years later refuted Von Buch's influential theory of craters of elevation. In 1887, Dana returned to Hawaii for the summer to make further observations and soon published the book, *Characteristics of Volcanoes,* which emphasized Hawaiian examples and offered the prophetic suggestion that the islands should become popular with tourists (Dana, 1890d).

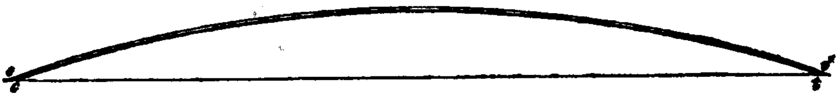
To Dana, igneous activity, especially as manifested in volcanism, provided clues to the "interior vital forces" of the Earth, which in turn produce the "grand outline features" of the Earth just noted. He assumed, as practically everyone had since the 17th Century cosmogenies of Descartes and Leibnitz, that the Earth began as a molten sphere, and as it cooled it must contract. Because the moon lacks a hydrosphere and atmosphere, he looked to it for analogies of the Earth's early cooling history. In his first paper about tectonics, *On the Volcanoes of the Moon,* Dana argued that "contraction from cooling would take place most rapidly over the thinner and more yielding volcanic portion [of the globe]." Because few volcanoes occur today within continental interiors, he concluded that "the continents were first free from eruptive fires" (1846, p. 353) and so must have cooled first. Conversely, the Earth's ocean basins with their many volcanoes both within and at their margins are still actively cooling. With a characteristic style of posing rhetorical questions, Dana then asked "What has given the continental portions of our globe their elevation . . . if not the unequal contraction of the whole?" (p. 354). He concludes the 1846 paper with "The greater subsidence of the oceanic parts would necessarily occasion that lateral pressure required for the rise and various foldings of the Alleganies and like regions." (p. 355). Dana acknowledged in a footnote (p. 355) that the theory of changes of elevation by contraction had been presented earlier by Babbage, De la Beche, and Prevost but implied that he had arrived at the idea independently–a not uncommon Danian claim.

Like many of Dana's papers, his next one (1847a) reads like an extended abstract of seven pages, two of which are in outline form with a numbered and lettered list of "facts." New points include the suggestion of an unequal rate of subsidence due to gradual strain and sudden fracture, causing a spasmodic history and even the possibility that an area might oscillate between emergence and drowning. Similarly, due to differential responses to strain, portions of a continent might rise while others subsided. Farther on, Dana applied his scheme to North America, noting especially the Appalachian folding documented recently by the Rogers brothers (Rogers and Rogers, 1843). They were the first to show that a system of folds was the result of a consistent stress across an entire mountain belt with more intense compression, slaty cleavage, and metamorphism on one side; they also described what would today be called thrust faults. Although Dana accepted their factual data, he did not endorse the Rogers' hypothesis to explain the folding. In the tradition of France's Elie de Beaumont, they postulated a great shock wave propagating through a liquid subcrust to wrinkle the overlying crust. To Dana, however, the eastward increase of intensity of folding is "as should be expected . . . nearest the ocean." And "another result of proximity to the contracting area, [is that] the rocks on the eastern side have been most altered by fire. [In fact] it is difficult in New England to distinguish the true igneous rocks from those that are metamorphic." (Dana, 1847a, p. 98). Dana then presented a similar analysis of the Pacific side of the continent and concluded "Thus each great oceanic depression, the Atlantic and Pacific, has its border range of heights thrown up by the very contraction which occasioned the depression; and between lies a vast plain, scarcely affected at all by these changes, the great central area of the continent." (p. 98). This discussion closed with the following statement: "If these conclusions are correct, we must give up the popular idea . . . of the elevation of mountains by a [vertical] force below causing at the time an irruption of igneous matter; for the irruption is in general an effect of a very different action, as has been urged by Prevost." (p. 99). As an addendum with implications of design, he noted the following economical advantage: "Silurian rocks indicate that before the coal period the region was comparatively level, and lay mostly beneath the sea. As it emerged it was still dripping with water, so that, under a climate peculiarly genial, coal vegetation might have grown luxuriantly." (p. 100).

Dana's next paper (1847b) continued the discussion of geological results of contraction, but added little new except for some diagrams and interesting rhetoric. He provided three figures, which summarize nicely his view of the progressive effects of oceanic subsidence due to global contraction (fig. 2). He also presented three figures showing Appalachian folding and again concluded that the asymmetry of the undulations are "necessary results of a force laterally exerted" (p. 183) rather than a vertical force, which he had characterized as "the most incredible of geological dogmas" (p. 179). Among ten items in a list, Dana noted that igneous rocks intruded into folded beds need not be

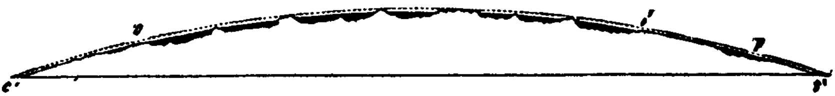
The principles may perhaps be rendered more clear by means of the following figures. In fig. 1, the crust (*ct*) is represented covered with wa-

Fig. 1.



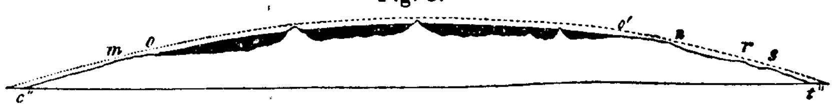
ter (*oo'*). In fig. 2, the globe has contracted from the dotted line to *c't'*; *c'o*, *o't'*, are the portions free from volcanic action, (as was the case almost entirely with the parts corresponding to the continents in the Silurian period;) *p* is an area of wa-

Fig. 2.



ter upon *o't'*. *oo'* represents the incipient oceanic depression, over which, owing to its igneous character and thinner crust, (this Journal, ii, 352,) contraction went on the most rapidly, and where, at the same time, igneous ejections and displacements (which result from contraction beneath the crust, causing a drawing down of the crust upon a diminishing nucleus) were frequent. It is evident that the depression would at first be too shallow to contain all the water; but as subsidence proceeded, and most rapidly over the oceanic areas, the capacity of the cavity would increase and tend to drain the forming continent. This result might, however, be long delayed by the eruptions and upliftings throughout the area *oo'*, an effect which would diminish the capacity of the oceanic basin, and so compensate for the contraction going on. The land would finally emerge; but the same causes (eruptions and upliftings over the oceanic areas) might make the water rise over it again, and occasion for ages, successive submergings and emergings of the continents. Temporary cessations of subsidence over the oceanic areas might take place from increasing tension preceding a paroxysmal relief by fractures, and this would be another cause of a rise and fall in the water level.

Fig. 3.



As the crust below the oceanic depression becomes thicker by cooling, the contraction, not now causing fractures and upliftings over its own area alone, would produce a tension laterally against the non-contracting area and occasion pressure, fissures, and upheavals; and thus the elevations *m*, *n*, *r*, *s*, fig. 3, would result.

Fig. 2. Figures from Dana's 1847b paper (p. 183) showing three stages in the contraction and subsidence of the cooling Earth. The original captions are included for completeness.

the cause of plication but rather may be another effect of deformation. Thus the parallel trap dikes seen from New Jersey to Nova Scotia were igneous eruptions thought to have accompanied the elevation of the Appalachian Mountains, that "grand crisis" characterized by "violent shakings of the globe" and "vibrations in the oceans," which was "a necessary result of the contraction in progress" (p. 187).

The third 1847 paper discussed the "Grand Outline Features of the Earth," such as coast lines, island groups, and mountains (Dana, 1847c).

Dana first elaborated the evidence for two recurring trends (northwest and northeast), then presented a numeric list of variations among trends, and finally gave a lettered list of conclusions about them. Rectilinear, intersecting trends were discussed with reference again to several European advocates of a *law of parallelism* between "cleavage joints" and larger features such as mountain ranges. Dana referred approvingly to a theory of British mathematician William Hopkins, which argued that two, more or less perpendicular directions of fracture are to be expected for regions under a state of tension. Dana concluded that "Whatever the origin, there can be no doubt of the *fact*, that a kind of cleavage structure . . . was given the crust during its formation, and that such a structure has influenced the direction of the lines of fissures that have since taken place" (p. 395, emphasis his). Of course the origin of such structure was attributed to contraction, which Dana thought the only cause that could explain "the frequent curvilinear forms of ranges" (p. 396).

The last of the 1847 outpouring, a paper of only five pages (1847d), is almost entirely in outline form. It is a summary of all the previous papers bearing upon Dana's global theory with citations to each; nothing new was added other than some of the rhetoric. Contraction as a consequence of solidification caused subsidence, which was greatest where the crust was thinnest and most yielding. The Earth's cleavage structure was determined by the position of those large areas of greatest contraction, and it in turn controlled the courses of mountains, coast lines, and thus continental form. Arching of the crust along zones that resisted subsidence resulted in tension and spasmodic fracture followed by abrupt subsidence. Continents are areas of least contraction, and the mountains formed along their borders are highest and have the most volcanoes next to the largest, subsiding ocean. Igneous material would be injected along open fissures. "The general forms of continents, and those of the seas . . . were to a great extent fixed in the earliest periods by the condition and nature of the earth's crust. They have had their laws of growth, involving consequent features, as much as organic structures" (p. 92).

NORTH AMERICA–THE PERFECT, GROWING CONTINENT

It was eleven years before Dana again wrote anything significant about his global theory. His 1855 Presidential address to the American Association for the Advancement of Science, which was published twice (Dana, 1856a,b), gave a detailed account of the geologic history of North America. Early in the address, he made an eloquent pronouncement that geology is, first and foremost, a study of history, which demonstrates that the Earth is a great, evolving system. The address contained only a one-page sketch of America's tectonic framework (1856a, p. 311), but in this he declared "a grandeur in the simplicity" of North America (p. 329), while Europe "has ever been full of cross purposes," being much broken up into basins and mountain ranges of all ages. Therefore, America provides a "clearer exhibition of many geological principles."

Both versions of his Presidential address contain references to "omnipotent power" and "acts of omnipotence," but the version published by the

American Association for the Advancement of Science (1856a) contained a three-page preamble, which reads like a Sunday sermon. It is full of references to the revelations of God to be found in Nature; for example, "Nature becomes a living expression . . . of the perfection of the Supreme Architect" (p. 2). Science is exalted as the proper way to distinguish divine truths from human fancies. These pious introductory pages may have been Dana's opening salvo against classicist Tayler Lewis with whom he was to feud for the next two years about science versus religion. Consider Dana's passage "Says a recent writer, somewhat contemptuously, 'The philosopher knows no better the cause of the law of gravitation than the ignorant man'." (p. 1, paragraph 2). Lewis thought that science had nothing to say about the Bible and, furthermore, that it "occupied a place in the public mind out of all proportion to its worth" (in Sherwood, 1969, p. 313). He also had asserted specifically that "We can get along very well without geology; our intellectual and moral dignity would not have been impaired had no such science ever existed." (Lewis, 1855, p. 305). Dana's first nervous breakdown in 1859 may have been aggravated by Lewis' attacks upon science and an 1858 geological feud with Frenchman Jules Marcou (Rossiter, 1979, p. 123). The principal causes, however, were overwork and the deaths in close succession of a favorite brother and two of his own children. This breakdown occurred in the same year that *Origin of Species* appeared, and Dana informed Darwin that he was unable to read it because of his health (although he continued to write papers and revise his books). For the remainder of his life, Dana had to restrict his activities carefully; for example, he did not attend the annual meeting of the American Association for the Advancement of Science between 1854 and 1889.

Immediately following the *American Journal of Science* version of his address, Dana took up the subject of tectonics again in a fourteen-page paper, "On the Plan of Development in the Geological History of North America" (1856c; reprinted elsewhere verbatim in 1857). This paper contained one very important addition to the author's evolving theory, namely the idea of a growing continent from an *earliest germinant spot or primal area,* the Azoic rocks surrounding Hudson Bay (fig. 3). First the reader was treated to three numbered lists of topics. The first list elaborates the author's ideas about proximity to oceans. As a principle, the height of mountain ranges was correlated with the size of and distance to an adjacent ocean basin. He glossed over the great distance of the world's loftiest range, the Himalaya, from the modest-sized Indian Ocean and completely ignored the mountains of southern Europe and the Mediterranean region where he began his career. Two more consequences were stated, "The nearer the water, the hotter the fire" (that is, more volcanoes and greater metamorphism) plus "The nearer the water, the vaster the plications of the rocks" (1856c, p. 338). Dana then re-emphasized that the "profounder features of the Earth were marked out in the earliest beginnings of geological history" (p. 339), that continents have always been more elevated, and their interiors are nonvolcanic in contrast with oceans, clearly implying that both continents and ocean basins have been permanent features. This was an important novelty, for conventional

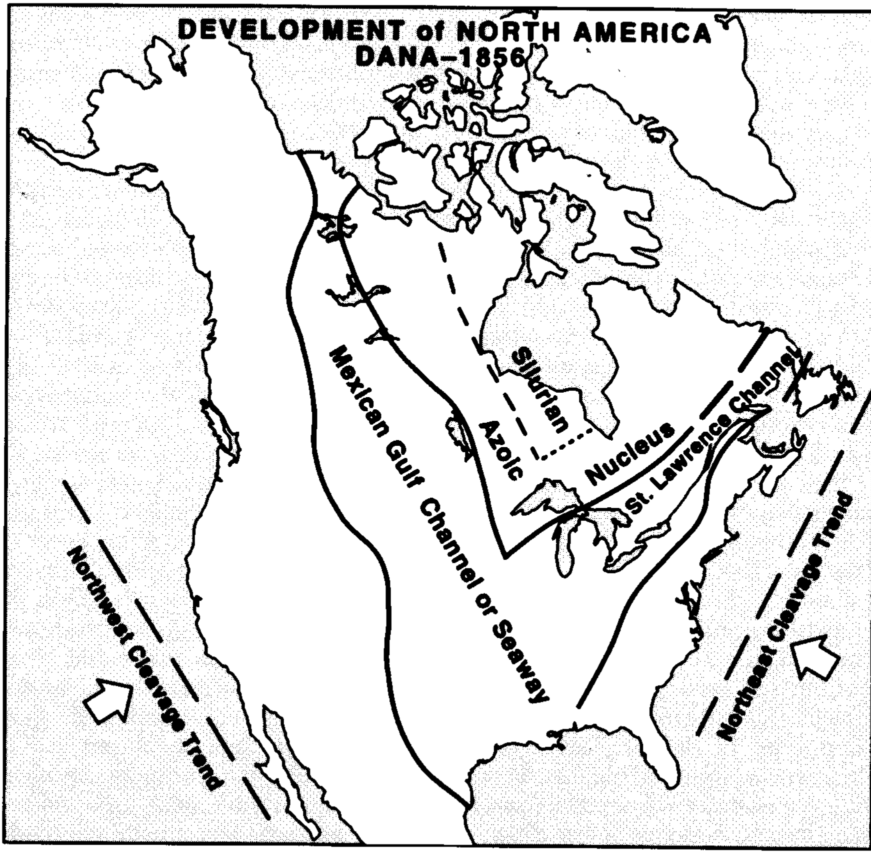


Fig. 3. Adaptation of plate 2 from Dana's 1856c paper showing the *Azoic germinant spot* or nucleus of North America as well as the Mexican Gulf and St. Lawrence Channels inboard from the western Cordillera and Appalachian Mountains respectively. The northwest (Pacific) and northeast (Atlantic) cleavage lines reflected by the continental margins have been added. "Silurian" in Canada indicates that the large outlier of strata of this age along the west shore of Hudson Bay was already known.

wisdom had long assumed that oceans and continents were interchangeable, like Atlantis.

Next we encounter more Danian rhetorical questions: "What then is the principle of development through which these grand results in the earth's structure and features have been brought about? We detect a plan of progress in the developing germ; we trace out the spot which is the first defined, and thence follow the evolution in different lines to the completed result: may we similarly search out the philosophy of the earth's progress?" (p. 340). He then restated that contraction has been the dominant power in forming the earth's lineaments. As the crust slowly thickened, it had acquired a regular structure much like ice crystallizing on a pond; perhaps feldspar, "the prevailing mineral in all igneous rocks," gives the cleavage structure observed in the crust (p. 340). Having already written metaphorically "from the first featureless sphere to the bold expressiveness and wrinkles of age," Dana invokes the venerable analogy between a contracting Earth and the wrinkles of a drying apple (original with Prevost, according to Greene, 1982).

After five pages of rambling, redundant review, Dana got around to the new idea of *continental growth or accession.* North America, because it is surrounded on all sides by oceans, has a triangular form with simple ocean boundaries and relatively simple geology, making it a near-perfect continent, thus a model or type example for continental evolution. Forces due to global contraction came largely from the southwest and southeast, and produced the northeast- and northwest-trending lineaments flanking the Azoic nucleus (fig. 3). "The evolution of the continent took place through the consequent vibrations of the crust, and the additions to this area . . ." (Dana, 1856c, p. 342). The long secular vibrations were considered essential to progress, for "Had the continent been [rigidly] stable, there could have been no history, no recorded events of changing life and alternating deposits" (p. 342). Thus did the continent expand or grow, mostly to the southward. The Azoic germ or nucleus had a V shape opening northward with two marine 'gulfs or channels' forming a larger V outside and parallel to it (fig. 3). These St. Lawrence and Mexican Gulfs lay between the nucleus and the bordering mountain systems of the continent. Following Hall, Dana stated that strata within the mountains are much thicker than contemporary strata in the interior gulfs. Moreover, he believed that the limestones of the gulfs were deposited in deeper water than the more sandy deposits found in the bordering mountain regions. Through time, the gulfs had gradually shrunk as the sea withdrew from the continent, the marginal mountains grew loftier, and rivers "were sent on their renovating missions [by spreading fertile alluvial plains] over the breadth of the continents" (p. 348). Thus an inevitable teleological conclusion was drawn that "those special details, were developed, that were most essential to the pastoral and agricultural pursuits with which man was to commence his own development, while that grandeur was impressed on the earth that should tend to raise his soul above its surface" (p. 348). "Thus, then, the continent was completed. Contraction was the power, under Divine direction, which led to the oscillations of the crust, the varied successions in the strata, and the exuviations of the earth's life, era after era . . . And finally . . . the surface received its last touches, fitting it for a new age–the Age of Mind" (p. 349).

JAMES HALL'S THEORY

Dana's story of continental evolution was not completed in 1856, after all, for James Hall in 1857 sprang his curious theory for the origin of mountains at the end of his Presidential Address to the American Association for the Advancement of Science. The actual address was not published until 1883, but during the next two years, Hall included a discussion of his theory in the Geological Survey of Iowa (Hall and Whitney, 1858), in the New York

Geological Survey report on Devonian paleontology (Hall, 1859), and a two and a half page summary appeared in Canada a year later (Hall, 1860). The 1859 version has been the standard source ever since. Hall was much influenced by a speculation by John F. W. Herschel published in 1837 as two letters in the Bridgewater Treatises (Herschel, 1837). Herschel postulated that vertical movements of the crust were driven by pressure and temperature changes at depth in response to surface erosion on the one hand and deposition on the other. He assumed that the interior of the Earth is pliable enough to yield easily to gravitational loading, resulting in a depression at one point and elevation at another. Furthermore, as sediments depressed the crust, they themselves would be heated as they sank to warmer depths.

Hall's original contribution to the question of mountain building was his recognition that Paleozoic strata are not only more deformed but also much thicker in the Appalachian Mountains than they are in the continental interior, the *craton* of modern terminology (Dott, 1985). Hall saw a simplistic cause-effect relationship such that more sediment could accumulate at the edge of the continent–the future site of the Appalachians–and that this accumulation would depress the crust by gravitational loading a la Herschel. As the strata accumulated, the resulting downwarping would cause the upper part of the sedimentary pile to be crumpled by compression (fig. 4), whereas the lower part would be fractured by extension; magma could be intruded along some of the fractures and the lower portion of the sedimentary sequence would be metamophosed by heat and pressure due to the deep subsidence. Thus, thought Hall, many of the characteristic features of mountain belts could be formed. In his own words: "The line of greatest depression would be along the line of greatest accumulation [that is] the course of the original transporting current. By this process of subsidence . . . the diminished width of surface above, caused by this curving below, will produce wrinkles and folding of the [upper] strata. That there may be rents or fractures of the strata beneath is very probable, and into these may rush the fluid or semi-fluid matter from below, producing trap-dykes; but the folding of strata seems to me a very natural and inevitable consequence of the process of subsidence." (Hall, 1859, p. 70 & 73). He thought that the sediments had been derived from the northeast and then carried southwest by the "transporting current" along the margin of the Paleozoic continent; moreover, the trend of the fold axes would correspond with the line of that current.

Hall divorced the topographic uplift of mountains from folding of the strata. He thought elevation was of continental, rather than local, origin because the Appalachians are not significantly higher than the adjacent Alleghany Plateau, which is underlain by flat-lying Paleozoic strata (that is, part of the craton). The mechanism of such uplift was not specified, but he did note that the highest mountains of the world contain very young strata, implying to him that they had received greater accumulations through longer time. Because gravitational buoyancy is implied, the Herschel-Hall hypothesis amounts to an embryonic isostatic mechanism for mountains (Mayo, 1985). Hall side-stepped any further specification of physical mechanisms by

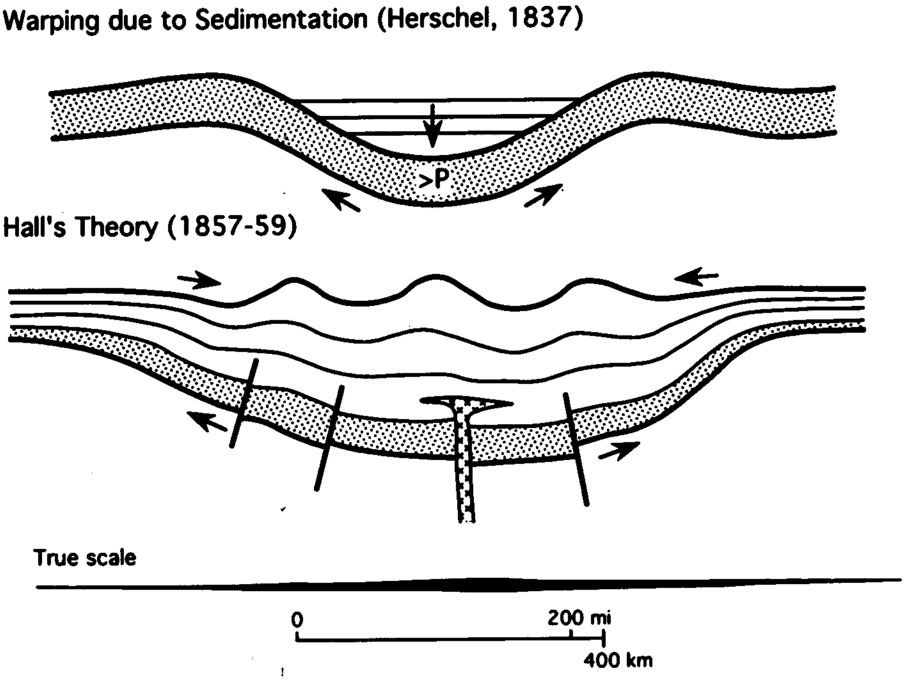


Fig. 4. The Hall-Herschel theory of downwarping and deformation due to the weight of a thick accumulation of strata. Hall envisioned that the upper layers would be crumpled due to compression resulting from the decrease of their circumference, while the lower layers would be broken by tension as their circumference was increased by downbending. Igneous dikes could be intruded along some of the tensional fractures. (Redrawn from Dott, 1985, fig. 5).

declaring that it had never been his intention to present a complete theory of mountains.

Hall's theory was endorsed by T. Sterry Hunt (1861, p. 411), who added the suggestion that *condensation,* "which must occur when porous sediments are converted into crystalline rocks like gneiss . . . and when the elements of these sediments are changed into minerals of high specific gravity," facilitates contraction and folding of strata. This takes place where sediments are deeply buried and are softened by metamorphism. Hunt rejected the notion of igneous fluidity for the Earth's interior but postulated as the source of magmas a zone of plastic sedimentary material raised to a high enough temperature to become more or less in "igneo-aqueous fusion."

Dana acknowledged Hall's claim of greater subsidence in the Appalachian region during sedimentation as "established by shallow-water markings in most of the successive strata, from the bottom to the top of the Paleozoic" (Dana, 1866, p. 207). As a consequence, "The subsidence connected with the formation of the successive thick deposits of sediments in the Appalachian region was, then, a foot-per-foot movement . . . a foot of sinking for a foot of accumulation." (p. 208). Dana reasoned that such would require a very thin, yielding crust with a perfectly mobile liquid beneath. Given the estimates by theorists of a solid crust 800 or so miles thick and a "densely viscid or solid interior," Dana found Hall's theory difficult to believe. "We may well question whether the earth, as long as its crust was so sensitive to the weight of a layer of gravel, would anywhere be able to hold up mountains; for mountains have gravity as well as gravel beds or other sediments." (p. 209). Moreover, most of the "bold flexing of the Appalachian rocks" took place after the Paleozoic strata had been deposited, rather than progressively during their deposition. In short, "Mr. Hall's hypothesis has its cause for subsidence, but none for the lifting of the thickened sunken crust into mountains. It is a theory for the origin of mountains with the origin of mountains left out." (p. 210).

Dana concluded his 1866 critique of Hall's theory with a paragraph hinting his own theory. He reminds the reader that mountains are situated along the borders of continents where strata have their greatest thickness and evidence of "great yieldings in the crust . . . through long ages . . . [and] where earthquakes show that today these are still the areas of greatest and most frequent movements" (Dana, 1866, p. 210-211). Whereas the thickest sediments–thus greatest weight to be lifted–present a serious obstacle to any theory postulating elevation directly from beneath, this is not a problem if the force is lateral action in a contracting crust. In an appendix to his paper (p. 252-253), Dana suggested that a further weakness of Hall's theory was the lack of a satisfactory explanation of the metamoprhism seen in parts of the Appalachians. He cites several areas where faults are known to have offset 15,000 to 20,000 feet of strata, yet the older, formerly deeper, strata show virtually no metamorphism, which discredits the Hall-Herschel appeal to the geothermal gradient alone for metamorphism by burial. Seven years later, he speculated that metamorphism was "due to motion or fermentation and pressure, aided by a moderate increase of temperature, producing chemical change." (Dana, 1873a, p. 348)

Joseph LeConte next entered the fray with a "Theory of the Formation of the great Features of the Earth's Surface" (LeConte, 1872). He first challenged the prevalent idea of Dana and others of a largely liquid Earth interior. Then he anticipated the upcoming theory of isostasy by arguing cogently that, if it were liquid, then necessarily the higher standing continental crust would have to be thicker than oceanic crust. Instead, he endorsed the views of British physicists Hopkins and Thomson that the interior is "substantially solid," and that the Earth has undergone unequal contraction by conduction of heat. "*Mountain chains are the lines along which yielding of the surface [*has occurred by*] mashing or crushing together horizontally like dough or plastic clay, with foldings of the strata, and an up-swelling and thickening of the whole squeezed mass.*" (p. 354; emphasis by LeConte). Finally, LeConte called upon the conversion of mechanical into thermal energy to produce local igneous fusion.

DANA AND THE GEOSYNCLINE

In 1873, Dana returned to global tectonics in a series of six linked papers in the *American Journal of Science.* Of his many tectonics papers, these have been referred to most frequently (Kay, 1951; Dott, 1974, 1979; Mayo, 1985). The first article of only four pages, "On the Origin of Mountains" (Dana, 1873a), restated the flaws in Hall's hypothesis, stressing especially that thick strata could not be the cause of mountains but that both are consequences of some other fundamental cause. Again he concluded that Hall's hypothesis for mountains lacked an acceptable mechanism for the elevation of mountains. This article apparently was intended as an introduction to the following, five-part article, "On some Results of the Earth's Contraction from cooling, including a discussion of the Origin of Mountains, and the nature of the Earth's Interior" all published during 1873. Part I (1873b) first summarized the earlier papers of 1846, 1847, and 1856 on contraction and the buckling of continental margins to elevate mountains. Dana then presented a section on some characteristics of the Appalachian mountain system and therein coined several important terms long associated with his theory. A *geosynclinal* (p. 430) was an "earth syncline" or large-scale downbending in the Earth's crust characterized by a long history of subsidence; it was clearly inspired by Hall's recognition that Paleozoic strata are much thicker within the Appalachian mountains than to the west (fig. 5). The *geanticlinal* (p. 432) was defined simply as a large, upward bending of the Earth's crust. At least 30 yrs before, the eastward-coarsening of many Paleozoic clastic strata had been recognized by Appalachian workers such as the Rogers brothers, so the idea of a complementary *geanticlinal* forming early on the oceanic side of the *geosynclinal* was accepted quickly (fig. 6). A *synclinorium* was defined as a mountain range formed from a geosynclinal by "a catastrophe of plications and solidification . . . metamorphism and igneous ejections are incidental results" (p. 431-432). In other words, "The *synclinoria were made through a progressing geosynclinal*" (p. 432; his italics). An *anticlinorium* was defined as "produced by a *progressing geantilinal.* The geosynclinal ranges or synclinoria have experienced in almost all cases, since their completion, true elevation through great geanticlinal movements" (p. 432). Examples cited included a geanticlinal uplift of much of New England and of the Rocky Mountain mass in late geologic time, as well as the Cincinnati uplift on the opposite side of the Appalachian mountains (p. 432-433). This discussion was concluded with the following restatement of continental accretion: "the completion of a synclinorium has generally consisted in the solidification as well as plication of the rocks, and the addition of the whole mountain region to the more stable portion of the earth's crust . . ." (p. 433). By 1873, increasing knowledge added complexity, for Dana now had to discuss a break between the Lower and Upper Silurian rocks in eastern North America (p. 435-436), which reflected another structural disturbance (Taconian orogeny) with a counterpart known in Europe (presumably the Caledonian orogeny). Recognition of this break, in addition to the long-recognized terminal Paleozoic *Appalachian revolution,* a term coined by Dana and still in use today, made the history of eastern North America more complicated than Dana had thought before.

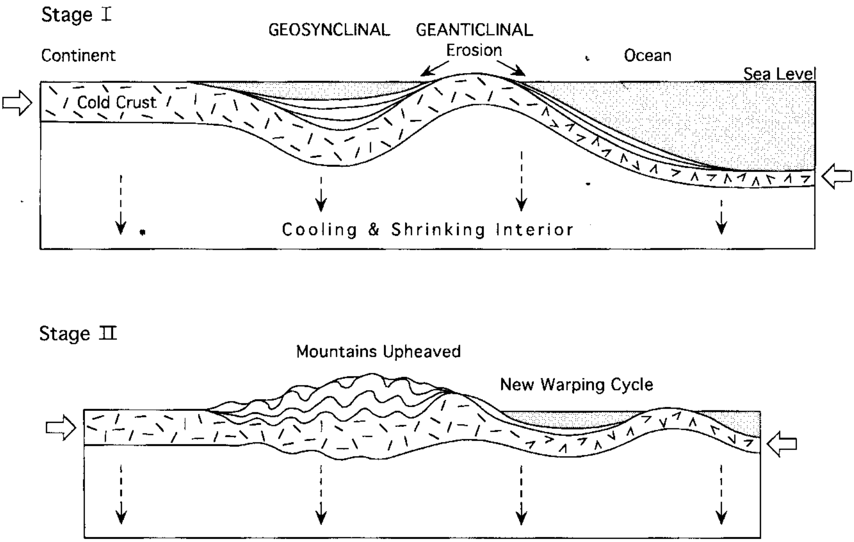


Fig. 5. Graphic summary of Dana's theory of mountain building at the margin of a continent due to thermal contraction of the globe. In the first stage, broad down-warping formed a *geosynclinal,* which was a repository for thick sediments derived largely from erosion of a complementary *geanticlinal* upwarp. Ultimately, the crust could bend no more, and the geosynclinal strata were crumpled and raised to form mountains, which were accreted to the continent. A new warping cycle then formed a new geosynclinal-geanticlinal couplet oceanward of the new mountains. (Adapted from Dana's verbal discussions of 1873).

Advances of knowledge of western North America since his 1840s and 1850s writings are also reflected by a lengthy application of the theory to that region.

Part II was titled "The Condition of the Earth's Interior" (1873c). In it, Dana discounted the existence of large volumes of vapor in the interior, whose sudden escape had been proposed as one means of elevating mountains. The slow sinking of the Appalachian geosynclinal recorded by 35,000 to 40,000 feet of Paleozoic strata required instead a liquid or viscous interior, which could be driven laterally away from the subsiding region to push up an adjacent, compensating geanticlinal. Thus lateral pressure due to global contraction "produced not only the subsidence of the Appalachian region through the Paleozoic, but also, contemporaneously, and as its essential prerequisite, the raising of a sea-border elevation, or geanticlinal, parallel with it; and that both movements demanded the existence beneath of a great sea of mobile rock" (1873c, p. 10). Moreover, the sea-border geanticlinal was postulated to have been the source for much of the sedimentary material deposited in the geosynclinal (figs. 5 and 6). "Part III. On Metamorphism" was printed with part II and was only two pages. Dana repeated his earlier contention that subsidence alone could not achieve enough heating of strata to cause their metamorphism; even a temperature of 800°F estimated by

PLATE XI

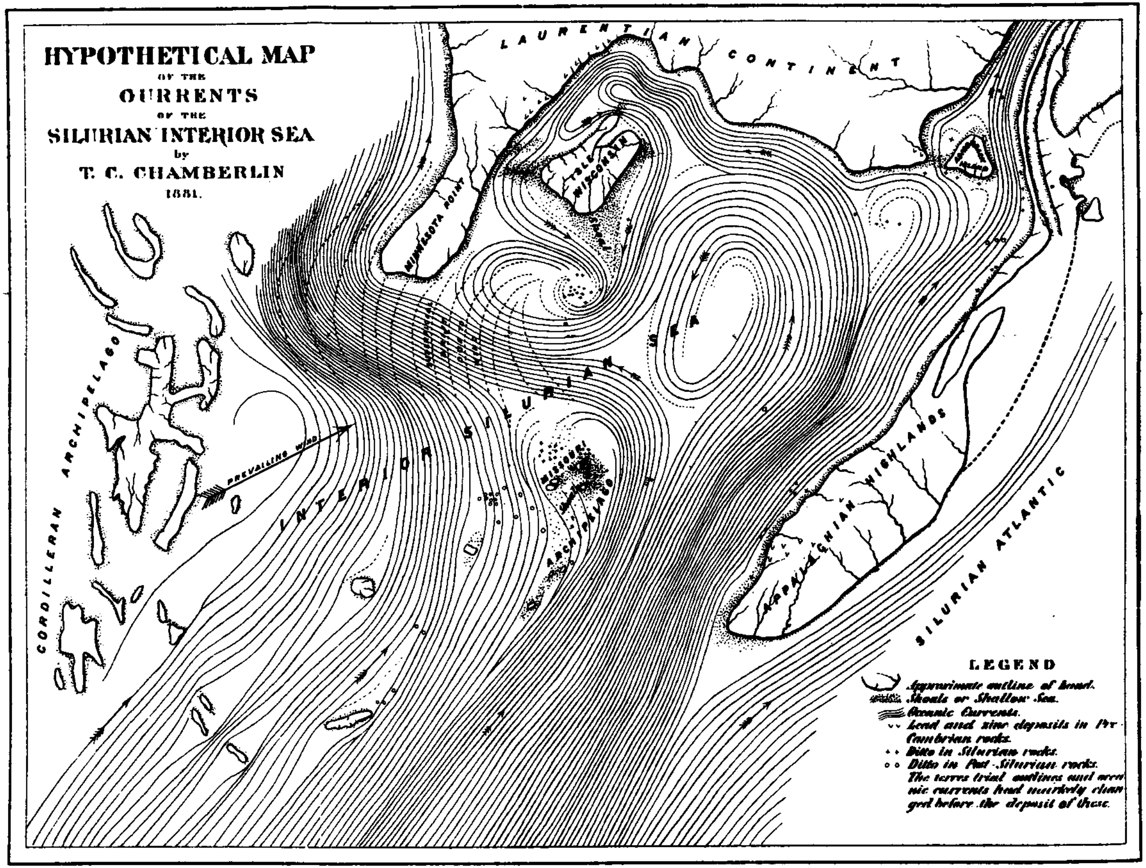


Fig. 6. The first paleogeographic map for North America (Chamberlin, 1881, p. 530) showing an eroding geanticlinal, the "Appalachian Highlands," as originally postulated by Dana along the eastern margin of the continent and amplified later by Walcott (1891) and Williams (1897). The map actually shows Cambrian paleogeography, but in 1881, all the lower Paleozoic was still classed as "Silurian."

LeConte (1872) for the base of the seven-mile-thick Paleozoic strata of the Appalachians was judged insufficient. Instead, Dana restated his advocacy of the increasingly popular idea that the necessary added heat was generated as the strata were being folded "according to the principle of the transformation of motion into heat." (p. 14), an apparent concession to LeConte; moisture in the rocks also was thought to facilitate metamorphism.

In "Part IV. Igneous Ejections, Volcanoes" (1873d), Dana appealed to the already-postulated, sub-crustal viscous zone as the source of most magmas. Such a vast "under-crust fire-sea" (p. 108) was deemed a necessity to explain "the great heavings and bendings of the earth's crust essential to mountain-making" (p. 112). Because "A doleritic or basaltic character is the prevailing one among the igneous eruptions of all ages from Archaean time to the present" (p. 110), Dana inferred that material of this composition must consitute the deeper crust or sub-crust. He saw an inverse relationship between the intensity of folding and metamorphism on the one hand and fissures and igneous ejections on the other. Igneous ejections (including intrusions) were facilitated by the lateral pressure causing the subsidence of a geosynclinal, but "ordinary volcanoes" might owe their eruptions largely to the expansion of vapors rising with the lava (p. 115).

"Part V. Formation of the Continental Plateau and Oceanic Depressions" (Dana, 1873e) was primarily a summary of new advances in igneous petrology, especially the recognition of the basic and acidic igneous clans, and an attempt to apply this knowledge to the origin of the crust of both ocean basins and continents. It was not very successful and added little to Dana's theory. For example, it began with the following bit of tangled reasoning "The *fact* of unequal contraction is manifest from the inequality of level that exists over the sphere dividing it into oceanic depressions and continental plateaus; and unequal contraction, the material of the crust being essentially the same over the two kinds of regions, implies an unequal rate of cooling" (1873d, p. 161). Overall uniformity of crustal composition stated in this paper seems to contradict his early emphasis on the uniqueness of oceanic crust. Seemingly he had in mind here that the original crust was everywhere doleritic or basaltic, but, by implication not specification, continents had subsequently acquired a more complex (and more acidic) crust. He repeated his 1846 and 1847 conclusion that the crust beneath continents had cooled early and had become relatively stable, while oceanic areas cooled much more slowly and formed depressions due to unequal contraction. Some new ideas about continent making appear in this paper; for example, as the continents solidified, their slightly greater density would cause them to sink gravitationally into the assumed underlying liquid layer, thus squeezing some liquid material upward "to flow over the solidifying area and add to the solidifying material" (p. 167). He also restated his 1847 speculation that feldspar cleavage planes in the first-formed crust may have given rise to the global cleavage lines (p. 169). Another notable feature of this article is the last section titled "The Continents always the continental areas," which asserts that "the oceanic and continental areas were defined when the earth's crust first began to form" and "It is hardly possible to conceive of any conditions of the contracting forces that should have allowed of the continents and oceans in after time changing places . . ." (p. 170).

The Conclusion for the last article of 1873 was an updated, concise list of all the essential elements of Dana's global theory. Paraphrasing the highlights, we learn the following: that mountain making occurs at continental borders because oceanic crust has the advantage through its lower position of *leverage* or upthrust against the continent; that great mountain chains are combinations of synclinoria and anticlinoria; that (following LeConte) plication, shoving along fractures, and crushing are the sources of elevation with thermal weakening of the deeper parts of the geosynclinal facilitating its destruction; that on the oceanic side of the geosynclinal, a geanticlinal generally appears early and then disappears; that each epoch of mountain-making ends in annexing the region to the stiffer part of the continent, and afterward a new geosynclinal forms outside the former crumpled one (see fig. 5); that igneous eruptions and metamorphism are greatest where (or after) the crust becomes most stiffened (that is, more brittle); and that metamorphism may produce "the pasty fusion which obliterates all stratification and gives origin to granite" (p. 171-172). Perhaps most significant was the statement "If this was true for the North American continent, the same in principle was law for all continents" (p. 170).

MOPPING UP

Dana's last commentaries on global tectonics appeared in an 1889 article on deep oceanic troughs, three 1890 articles on "Archaean protaxes," and in the fourth and last edition of *Manual of Geology,* which appeared in 1895, the year of his death. The 1889 paper described a new bathymetric map of the world, which provided the base for figure 1 of the present paper, and posed the question "Are the deep troughs volcanic in origin?" Dana answered "probably not." Nothing new was added to the global theory, but again he called attention to the "feature-lines" of the Earth (formerly called *cleavage lines*).

All three of the rather ambiguous 1890 articles concern what Dana regarded as a refinement of the understanding of mountain systems, and, by implication, of geosynclinals. My own assessment is that the new concept of *Archaean protaxes* presented therein obfuscated more than refined the theory. The first paper (1890a) outlined the general idea that long zones or ridges of presumed Archean crystalline rocks seen today near both the eastern and western margins of the continent were of very early origin and helped to confine the Paleozoic and Mesozoic inland continental seas. Dana thought he had found yet another Archaean fingerprint. "The facts illustrate strikingly the great truth that the earth's features even to many minor details were defined in Archaean time, and consequently that Archaean conditions have exercised a special and even detailed control over future continental growth" (1890b, p. 383). This glossed over the fact that the so-called embryonic or proto-axes of the Appalachian and Rocky Mountain systems lay respectively *east of* (outside) the main Appalachian ranges but *along the axis of* the western mountains, so were not similar in their relationships to their respective mountain belts. The other two articles addressed in more detail each of these protaxes respectively (1890b,c). The protaxis concept reflects a common fallacy in 19th Century geological thinking, which assumed simplistically that present outcrop distributions faithfully represent the ancient distributions of those same rocks. Thus Dana's paleogeographic maps for the end of Precambrian ("Archaean") and the earlier half of Paleozoic time show "dry land" wherever Precambrian rocks are exposed today, including his long, narrow "protaxes" (1895, p. 443 and 536).

The new concept of Archaean protaxes, which apparently had its roots with T. Sterry Hunt (Dana, 1890c, p. 9), added further complication to Dana's theory, for the postulated ancient ridges subdivided the "great subsiding Appalachian trough [geosynclinal], or group of troughs" (p. 42). Whereas previously he had envisioned geanticlinal lands as genetic couplets with geosynclinals, the protaxes apparently pre-dated the geosynclinals, and therefore no longer had a clear causal relationship with them; only the Cincinnati axis west of the Appalachian trough was still referred to as a geanticline. Moreover, what formerly seemed to be a single, sea-border geanticlinal land east of the Appalachian geosynclinal (fig. 6), which had been considered the principal source of Paleozoic sediments (1873c, p. 9-10), had now become a series of ridges, and Dana suggested other sources for the geosynclinal sediments. Charles Walcott (1891), while accepting the notion of "the outlying ridges," still regarded them as a major sediment source, even suggesting that much of the ancient border land now lies beneath the Atlantic coastal plain (p. 365). Dana's original concept of a geanticlinal borderland linked to the geosynclinal and composed largely of Precambrian basement rocks was revived and more fully formulated by H. S. Williams (1897) with the naming of *Appalachia* as the eastern land that provided the Devonian Catskill clastic sediments. Most of the rocks lying east of the folded Appalachians were metamorphic and plutonic crystallines like those of Dana's New England homeland, which were assumed to be largely Precambrian (and still so shown on the Geologic Map of the United States as late as the 1930s), although widely-scattered meta-sediments containing Paleozoic fossils were known. Thus the eminently logical concept of a Precambrian borderland was to rule over American geology for 50 yrs.

In Dana's last major publication, the fourth edition of the *Manual of Geology* (1895), *Archaean protaxes* and *synclinoria* were featured, but not *anticlinoria.* Most significantly, *geosyncline* and *geanticline* were finally converted to the noun forms familiar to later generations. I could find no explanation by Dana for this change, but it clearly occured between 1890 and 1895. The *Manual* contains a concise summary of the contraction theory of mountain-making, which can be taken as Dana's ultimate statement on his global theory. Besides the addition of Archaean protaxes and a more detailed knowledge of Appalachian history, new theoretical analyses by several physicists (Britons M. Reade, C. Davison, and G. H. Darwin, and Russian M. P. Rudiski) were said to support contraction. Dana estimated both rates and duration of subsidence in the Appalachian region and repeated the long-standing view from Herschel that the lower portion of the geosyncline would be heated sufficiently to soften and perhaps even melt. Continuing pressure due to global contraction would cause earthquakes, volcanic explosions, and the collapse of the weakened geosyncline, so that its strata would be flexed into anticlines and synclines traversed by oblique fractures (faults). Because of asymmetric contractive pressure against the continent, the flexures were more crowded on the oceanic side. As always, Dana used the Appalachians to illustrate the theory. He noted that Lower Silurian (Ordovician) uplift occurred within the "preparatory geosyncline" due to the "Taconic mountain-making crisis" (Dana, 1895, p. 386). This event was accompanied by the elevation also of the low Cincinnati geanticline to the west of the geosyncline and an eastern geanticline, which emerged and persisted until Cretaceous time from New York southwestward beyond Virginia (p. 387). The Appalachian revolution at the end of the Carboniferous and further Triassic and Jurassic deformations completed the orogenic development of eastern North America; denudation then sculpted the topographic mountains seen there today. Subsequent discussion concerned continents and mountain systems in general, with restatements of Dana's rule that the width of oceans controls the magnitude of mountains and that North America is the type-continent, which best displays continental growth. Finally, there was an up-dated summary of speculations by various authors about global patterns or feature-lines, but these did not affect Dana's commitment to contraction as the ultimate cause of mountains. Neither did the new theory of isostasy bother him, for he regarded it as "earth shaping in its action, without being mountain-making" (Dana, 1895, p. 374).

AFTER DANA, WHAT?

Dana's paradigm was one of the first major theoretical contributions to geology from America, and it had significant impact abroad as well as at home. The Rogers brothers' earlier discussions of Appalachian structure had attracted much attention in Europe (Rogers and Rogers, 1843) and paved the way for Dana's more globally encompassing theory. In North America, the theory influenced thinking for nearly a century with several aspects being recognizable at least into the 1950s. His advocacy of permanence of continents undoubtedly contributed to American resistance to continental drift, for the geology of his simple, platonic North American continent seemed adequately explained by in-place continental accretion; drift simply did not offer any explanatory advantages. Abroad, the great Austrian tectonicist, Eduard Suess, while discounting the Hall-Dana hypothesis that a "preparatory geosyncline" was a prerequisite for mountain-making, cited favorably several other aspects of Dana's theory. Suess, too, was profoundly influenced by the evidence of Pacific subsidence, from which he concluded that warping down and up of ocean basins explained worldwide (eustatic) sealevel changes. Suess also focussed attention upon modern volcanic archipelagoes and their trenches by drawing analogies with ancient mountain systems (Suess, 1885-1909). He proposed that a foredeep (analogous with modern trenches) was warped down in front of rising, embryonic mountains (analogous with archipelagoes). He reasoned further that successive mountain-foredeep couplets were pushed outward from continents in successively younger, concentric rings–clearly in harmony with Dana's continental accretion. There were important long-standing differences between European and American thinking, however. These included the apparent origin of the Alpine geosyncline as a deepwater trough floored with oceanic crust (ophiolite) and located between two continents rather than marginal to a single one. Moreover, the clastic sediments were seen as shed from lands called *cordilleras* raised within the geosyncline and composed of nearly contemporaneous rocks rather than from borderlands raised outside and composed of much older rocks.

Thermal contraction was gradually discredited as the principal global tectonic driving mechanism during the early 20th century. Even if contraction had occurred, some authorities questioned its adequacy to deform and raise mountains, especially given the newly-recognized long distances of overthrust faulting, which required even greater crustal shortening. Moreover, the discovery of radioactivity in 1896 eventually raised doubts about simple, secular cooling, even though the magnitude of radioactive heating was slow to be appreciated. Meanwhile, the theory of isostasy had become accepted, and it seemed to those who had not actually mapped the intricately folded structures of mountain belts to offer an alternative orogenic mechanism through simple vertical uplift. T. C. Chamberlin came to the rescue of Dana's theory in the 1910s by substituting gravitational for thermal contraction in his planetesimal theory for the origin and evolution of the Earth (Chamberlin and Salisbury 1906; summarized in Greene, 1982, and Dott, 1992). This new theory, which was compatible with isostasy, continued to influence thinking through the 1920s. Chamberlin retained Dana's ideas of major global structural patterns, contrasts between continents and oceans, and the crumpling of continental margins to form mountains due to the interference between differentially subsiding continental and oceanic crustal wedges; the principal difference was that subsidence was driven entirely by gravitation.

Chamberlin's planetesimal theory had increasing competition after 1910. First, Taylor (1910) appealed to drifting and colliding continents to explain Cenozoic mountains and island arcs. Then Wegener amplified continental drift during the next 20 yrs (Wegener, 1929). In 1928 Holmes proposed that thermal convection in a viscous mantle could provide a mechanism for mountain building and, optionally, also for continental drift (Holmes, 1930). Except for the postulate of an expanding Earth (Carey, 1976), convection has remained the mechanism of choice for global tectonics during subsequent decades. It was invoked in a variety of specific theories, including the tectogene of Vening Meinesz and Kuenen (Kuenen, 1936-37), and was modelled by Griggs (1939). Only the new global tectonics manifested in the plate theory of the late 1960s brought a clear paradigmatic shift away from the ghosts of theories past, but convection survived this shift and quickly became a popular candidate for driving the plate motions.

Any new global theory had to explain the empirical phenomena recognized long ago by Hall, Dana, Suess, and their followers. The excessive thickness of strata in mountain belts and the requirement for some kind of land source for clastic sediments remained to be explained by any successful theory. So also did the genetic relationship between volcanic arc-trench systems and mountain belts as well as the secular addition or accretion through time of new continental crust as a byproduct of orogenesis.

It is a little-known fact today that the synthesis of these phenomena was already largely accomplished prior to the theory of plate tectonics. In petrology, it began with recognition of the significance of the *andesite line* (Marshall, 1912; Bryan, 1944). In geophysics, the first key was the discovery of the seismic focal zones beneath modern arcs (Gutenberg and Richter, 1938). These two fields then converged by linking specific earthquakes in this "Benioff zone" to specific volcanic eruptions at the surface (Benioff, 1954; Kuno, 1959). Such findings, coupled with measurements of gravity within island arc-trench systems (Vening Meinesz and others, 1934; Hess, 1938), strengthened the genetic linkage between modern volcanic arcs and ancient orogenic belts.

Meanwhile large volumes of Paleozoic volcanic rocks associated closely with meta-sediments containing marine fossils had been discovered within the Appalachian region (Williams, 1894; Billings, 1934; Kay, 1937) and in Wales (Fearnsides, 1910; Jones, 1938). Not only were the old borderlands not dominated by Precambrian rocks, they had not even been permanent lands. Rather they were oceanic areas within which ephemeral volcanic and tectonic islands–like the *cordilleras* long postulated by Alpine geologists–composed of contemporaneous volcanic, sedimentary, and plutonic rocks were raised intermittently. Such lands were the major sources of geosynclinal clastic sediments (Eardley, 1947; Kay, 1951; Dott, 1978). By the mid-1950s, the recognition of turbidity currents as a mechanism for the deposition of coarse clastic sediments in deep oceanic troughs largely completed the metamorphosis of the geosynclinal theory of Hall and Dana.

The quiet revolution about orogenic belts was partly eclipsed with the revival of continental drift by paleomagnetic data in the late 1950s, to be followed rapidly in the 1960s, first, by sea floor spreading and, then, by all-encompassing plate tectonics. The Benioff zone, volcanic arcs, and trenches were now to be explained by subduction; orogenesis was to be explained by subduction and collisions; while the geosyncline was demoted to a mere byproduct of "all of the above." The extension of the plate tectonic paradigm to pre-Mesozoic orogenic belts (Mitchell and Reading, 1969; Kay, 1969; Dewey and Bird, 1970; Dickinson, 1971) completed the global tectonic revolution, which has become the new geological orthodoxy of the last quarter of the twentieth century comparable in importance to the impact of Darwin's theory of natural selection in the last quarter of the previous century.

RETROSPECTIVE

James Dwight Dana belonged to the first generation of scientific specialists and was one of the first Americans to hold the title "Professor of Geology." During the same period, an American professional geological community took form (Newell, ms), and the contradictions between the findings of science and literal interpretations of the scriptures reached a crescendo. Dana, who had written that global contraction was under Divine direction (1856a, p. 349), was torn between his piety and his science. His most acute crisis came first with Taylor Lewis' vigorous attack upon science and then with Darwin's theory of evolution, which Dana belatedly and only partially accepted with great difficulty. It is ironic that Dana was such a champion of physical evolution of the Earth but such a reluctant acceptor of organic evolution. T. H. Huxley is said to have remarked that "Dana wrote with one eye on fact and the other on Genesis." Although he was an extreme case, Dana was by no means alone in his dilemma; he often shared his most private thoughts on religion and science with like-minded father-in-law Silliman, confidant Arnold Guyot, and Louis Agassiz. Prominence of the tension between religion and science in America led Alexander von Humboldt to suggest that "it was not safe for a man to pursue geology in the United States for fear of falling within the ban of the church" (Gilman, 1897, p. 185). In spite of much publicity, however, religion does not seem to have impeded the development of American geology (Newell, ms, p. 323).

The parallels of Dana's career with that of Darwin are legendary and have been recently summarized by Stoddart (1994) and Gould (1996). Equally interesting, but hitherto overlooked, are parallels in the subsequent career of T. C. Chamberlin. Besides rescuing Dana's global contraction theory, Chamberlin also edited an in-house journal for many years and liberally used its pages to review his versions of current issues and to present quasi-editorial papers on a wide range of topics; like Dana, he also groomed his son to take over the journal editorship. Both men viewed the practise of science with moral rectitude and saw as the ultimate purpose of science to provide a teleological account of nature's ordering for the progress of human life. Finally, Chamberlin was driven to synthesis as much as was Dana, and he was to succeed Dana in the early 20th century as America's most prominent geological theorist.

The simplicity of Dana's global paradigm and its incessant repetition over a half-century in diverse publications account largely for its lasting impact. No doubt Dana's vigorous declaration of independence from Europe also gave his American version of geology a strong nationalistic appeal. North America was pronounced the most perfect continent and several European traditions were challenged. The following two frontal assaults upon Lyell's approach are examples. First "Geology is a history, the records of which are written in the rocks: and such is its highest department. But is this clearly appreciated? If so, why do we find text-books, even the one highest in authority in the English language, written back end foremost,–like a History of England commencing with the reign of Victoria." (Dana, 1856a, p. 306). Second was Dana's rejection of ultra-gradualism with his emphasis upon *revolutions,* those brief epochs of rapid and profound geographical and biological changes, which punctuate geologic history as major time boundaries. For Dana, such revolutions were the quintessential expressions of a geologic unity connecting all aspects of the physical and biological evolution of the earth (Rice, 1914, p. 21).

The tectonic issues with which both Dana and Chamberlin wrestled hinged upon the most fundamental aspects of the Earth's remote interior. That neither of them, nor even a subsequent generation of scientists, could resolve those issues underscores the fact that no real breakthrough was possible until solid, empirical knowledge was gained about the physical and chemical nature of the deep interior. What were its compositional variations, temperature distribution, thermal conductivity, thermodynamic properties, rheological properties, and its structure? The need for such data was appreciated at the beginning of the present century when, for example, the Geophysical Laboratory was established in the new Carnegie Institution of Washington specifically to address such problems experimentally (Servos, 1983). No one could then predict, however, that three-quarters of a century more would pass before enough such knowledge could be gained to bring about a real theoretical revolution.

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REFERENCES

Appleman, D. E., 1985, James Dwight Dana and Pacific geology, *in* Viola, H. J. and Margolis, C., editors, Magnificent Voyagers–The U.S. Exploring Expedition, 1838–1842: Washington, Smithsonian, p. 89–118.

Beecher, C. E., 1896, James Dwight Dana: American Geologist, v. 17, p. 1–16.

Benioff, H., 1954, Orogenesis and deep crustal structure–additional evidence from seismology: Bulletin of the Geological Society of America, v. 66, p. 385–400.

Billings, M. P., 1934, Paleozoic age of the rocks of central New Hampshire: Science, v. 79. p. 55–56.

Bryan, W. H., 1944, The relationship of the Australian Continent to the Pacific Ocean–now and in the past: Journal of the Proceedings of the Royal Society of New South Wales, v. 75, p. 239–254.

Carey, S. W., 1976, The Expanding Earth: Amsterdam, Elsevier, 488 p.

Chamberlin, T. C., 1881, Geology of Wisconsin: v. IV, 779 p, and 25 plates.

Chamberlin, T. C., and Salisbury, R. D., 1906, Geology: New York, Holt, v. 1, 684 p.

Dana, E. S., 1895, James Dwight Dana: American Journal of Science, 3rd series, v. 49, p. 329–356.

Dana, J. D., 1835, On the conditions of Vesuvius in July, 1834: American Journal of Science and Arts, 1st series, v. 27, p. 281–288.

——— 1843, On the areas of subsidence in the Pacific, as indicated by the distribution of coral islands: American Journal of Science and Arts, 1st series, v. 45, p. 131–135.

——— 1846, On the volcanoes of the moon: American Journal of Science and Arts, 2nd series, v. 2, p. 335–355.

——— 1847a, On the origin of continents: American Journal of Science and Arts, 2nd series, v. 3, p. 94–100.

——— 1847b, Geological results of the earth's contraction in consequence of cooling: American Journal of Science and Arts, 2nd series, v. 3, p. 176–188.

——— 1847c, Origin of the grand outline features of the earth: American Journal of Science and Arts, 2nd series, v. 3, p. 381–398.

—— 1847d, A general review of the geological effects of the earth's cooling from a state of igneous fusion: American Journal of Science and Arts, 2nd series, v. 4, p. 88–92.
—— 1853, On Coral Reefs and Islands: New York, Putnam, 144 p.
—— 1856a, Address of Professor James D. Dana, President of the American Association for the Year 1854: Proceedings of the American Association for the Advancement of Science for the Year 1855, v. 3, p. 1–36.
—— 1856b, On American geological history: Address before the American Association for the Advancement of Science, August, 1855: American Journal of Science and Arts, 2nd series, v. 22, p. 305–334 (largely identical with the 1856a paper).
—— 1856c, On the plan of development in the geological history of North America, with a map: American Journal of Science and Arts, 2nd series, v. 22, p. 335–349.
—— 1857, Plan of development in the geological history of North America– with a map: Proceedings of the American Association for the Advancement of Science for 1856, v. 10, pt. II, p. 1–16 (identical with the 1856c paper).
—— 1866, Observations on the origin of some of the earth's features: American Journal of Science and Arts, 2nd series, v. 42, p. 205–211 and Appendix, 252–253.
—— 1872, Corals and Coral Islands: New York, Dodd and Mead, 398 p.
—— 1873a, On the origin of mountains: American Journal of Science and Arts, 3rd series, v. 5, p. 347–350.
—— 1873b, On some results of the earth's contraction from cooling, including a discussion of the origin of mountains, and the nature of the earth's interior; Part I: American Journal of Science and Arts, 3rd series, v. 5, p. 423–443.
—— 1873c, On some results of the Earth's contraction from cooling; Part II, The condition of the earth's interior, and the connection of the facts with mountain-making; Part III, Metamorphism: American Journal of Science and Arts, 3rd series, v. 6, p. 6–14.
—— 1873d, On some results of the earth's contraction from cooling: Part IV, Igneous ejections, volcanoes: American Journal of Science and Arts, 3rd series, v. 6, p. 104–115.
—— 1873e, On some results of the earth's contraction from cooling; Part V, Formation of continental plateaus and oceanic depressions: American Journal of Science and Arts, 3rd series, v. 6, p. 161–172.
—— 1889, On the origin of the deep troughs of the oceanic depression: Are they of volcanic origin?: American Journal of Science, 3rd series, v. 37, p. 192–202.
—— 1890a, Areas of continental progress in North America, and the influence of the conditions of these areas on the work carried forward within them: Bulletin of the Geological Society of America, v. 1, p. 36–48.
—— 1890b, Archaean axes of eastern North America: American Journal of Science, 3rd series, v. 39, p. 378–383.
—— 1890c, Rocky Mountain protaxis and the Post-Cretaceous mountain-making along its course: American Journal of Science, 3rd series, v. 40, p. 182–196.
—— 1890d, Characteristics of Volcanoes with Contributions of Facts and Principles from the Hawaiian Islands: New York, Dodd and Mead, 399 p.
—— 1895, Manual of Geology (4th edition): New York, American Book, 1086 p.
Dewey, J. F. and Bird, J. M., 1970, Mountain belts and the new global tectonics: Journal of Geophysical Research, v. 75, p. 2625–2647.
Dickinson, W. R., 1971, Plate tectonic models of geosynclines: Earth and Planetary Science Letters, v. 10, p. 165–174.
Dott, R. H., Jr., 1974, The geosynclinal concept, *in* Modern and Ancient Geosynclinal Sedimentation, S.E.P.M. Special Publication No. 19, p. 1–13.
—— 1978, Tectonics and sedimentation a century later: Earth-Science Reviews, v. 14, p. 1–34.
—— 1979, The geosyncline–first major geological concept "Made in America": Two Hundred Years of Geology in America: Durham, University of New Hampshire, p. 239–264.
—— 1985, James Hall's discovery of the craton: Geological Society of America Centennial Special Volume 1, p. 157–167.
—— 1992, T. C. Chamberlin's hypothesis of diastrophic control of worldwide sea level: A precursor to sequence stratigraphy: Geological Society of America Memoir 180, p. 31–42.
Eardley, A. J., 1947, Paleozoic Cordilleran geosyncline and related orogeny: Journal of Geology, v. 55, p. 309–342.
Fearnsides, W. G., 1910, North and Central Wales, *in* Geology in the Field: Geological Association of London, v. 2, p. 786–825.
Gilman, D. C., 1899, The life of James Dwight Dana–scientific explorer, mineralogist, geologist, zoologist, professor in Yale University: New York, Harper, 409 p.
Gould, S. J., 1996, This view of Life: What separated Darwin's transcendent greatness from James Dwight Dana's merely ordinary greatness?: Natural History, v. 105, p. 23–28 and 88–93.

Greene, M. T., 1982, Geology in the Nineteenth Century–Changing Views of a Changing World: Ithaca, New York, Cornell, 324 p.

Griggs, D., 1939, A theory of mountain building: American Journal of Science, 5th series, v. 237, p. 611–650.

Gutenberg, B. and Richter, C. R., 1938, Depth and geographical distribution of deep-focus earthquakes: Geological Society of America Bulletin, v. 49, p. 249–288.

Hall, James, 1859, Description and Figures of the Organic Remains of the Lower Helderberg Group and the Oriskany Sandstone: New York Geological Survey, Natural History of New York, Part 6, Paleontology, v. 3, Introduction, p. 1–96.

—— 1860, On the formation of mountain ranges: The Canadian Journal of Industry, Science and Art, new series, v. 5, p. 542–544.

—— 1883, Presidential Address to the American Association for the Advancement of Science: Proceedings of the American Association for the Advancement of Science for the Year 1882, v. 31, p. 29–69.

Hall, James, and Whitney, J. D., 1858, Report on the Geological Survey of the State of Iowa: Des Moines, State of Iowa, v. 1, pt. 1, p. 35–44.

Herschel, J., 1837, *in* Babbage, C., The Ninth Bridgewater Treatise: London, John Murray, Appendix, Note 1, p. 225–247 (Extracts from two letters to Charles Lyell and to Roderick Murchison, respectively, on speculations about crustal subsidence).

Hess, H. H., 1938, Gravity anomalies and island arc structure with particular reference to the West Indies: Proceedings of the American Philosophical Society, v. 79, p. 71–96.

Holmes, A., 1930, Radioactivity and earth movements: Transactions of the Geological Society of Glasgow (1928-29), v. 18, p. 559–606.

Hunt, T. S., 1861, On some points in American geology: American Journal of Science and Arts, 2nd series, v. 31, p. 392–414.

Jones, O. T., 1938, On the evolution of a geosyncline: Geological Society of London Quarterly Journal, v. 94, p. lx–cx.

Kay, M., 1937, Stratigraphy of the Trenton Group: Geological Society of American Bulletin, v. 48, 233–302.

—— 1951, North American Geosynclines: Geological Society of America Memoir 48, 143 p.

—— editor, 1969, North Atlantic-Geology and Continental Drift a symposium: American Association of Petroleum Geologists Memoir 12, 1082 p.

Kuenen, Ph H., 1936–37, The negative isostatic anomalies in the East Indies (with experiments): Leidsche Geologische Mededelingen, v. 8, p. 170–213.

Kuno, H., 1959, Origin of Cenozoic petrographic provinces of Japan and surrounding areas: Bulletin of Volcanology, v. 20, p. 37–67.

Leconte, Joseph, 1872, A theory of the formation of the great features of the earth's surface, American Journal of Science and Arts, 3rd series, v. 4, p. 345–355 and 460–472.

—— 1895, Memoir of James Dwight Dana: Bulletin of the Geological Society of America, v. 7, p. 461–479.

Lewis, Tayler, 1855, The Six Days of Creation, or, The Scriptural Cosmology with the Ancient Idea of Time-Worlds in Distinction from Worlds in Space: Schenectady, C. Y. Debogrot, 407 p.

Marshall, P., 1912, Address by the President: Reports of the Australasian Association for the Advancement of Science, v. 13, p. 90–94.

Mayo, D. E., 1985, Mountain-building theory: the nineteenth-century origins of isostasy and the geosyncline: Geological Society of America Centennial Special Volume 1, p. 1–18.

Mitchell, A. H., and Reading, J. G., 1969, Continental margins, geosynclines, and ocean floor spreading: Journal of Geology, v. 77, p. 629–646.

Newell, J. R., ms, 1993, American Geologists and Their Geology: The Foundation of the American Geological Community: Ph.D. dissertation, University of Wisconsin, Madison, 371 p.

Prendergast, ms, M. L., 1978, James Dwight Dana: The Life and Thought of an American Scientist: Ph.D. dissertation, University of California at Los Angeles, Ann Arbor, University Microforms. 625 p.

Rice, W. N., 1914, The geology of James Dwight Dana: Problems of American Geology, The Silliman Memorial Lectures: New Haven, Yale University, 42 p.

Rogers, W. B., and Rogers, H. D., 1843, On the physical structure of the Appalachian Chain, as exemplifying the Laws which have regulated the elevation of great Mountain Chains generally: Transactions of American Geologists and Naturalists for 1840–1842, p. 474–531.

Rossiter, M. W., 1979, A portrait of James Dwight Dana, *in* Benjamin Silliman and His Circle: Studies on the Influence of Benjamin Silliman on Science in America: New York, Science History Publications, p. 105–128.

Servos, J. W., 1983, To explore the borderland: The foundation of the Geophysical Laboratory of the Carnegie Institution of Washington: Historical Studies in the Physical Sciences, v. 14, p. 147–185.

Sherwood, M. B., 1969, Genesis, Evolution, and Geology in America before Darwin: The Dana-Lewis controversy: Cambridge, Massachusetts Institute of Technology Press, Toward a History of Geology, p. 305–316.

Stanton, W., 1981, Dana, James Dwight, *in* Dictionary of Scientific Biography: New York, Scribner, p. 549–554.

Stoddart, D. R., 1994, "This coral episode" Darwin, Dana, and the coral reefs of the Pacific: Darwin's Laboratory–Evolutionary Theory and Natural History in the Pacific: Honolulu, University of Hawaii, p. 21–48.

Suess, E., 1885–1909, Das Antlitz der Erde: Vienna, Tempsky, v. 1, 1885, 778 p.; v. 2, 1888, 703 p., v. 3, 1909, pt. 1, 508 p., pt. 2, 789 p. (1904-1924 English translations by H. B. C. Sollas: Oxford Press).

Taylor, F. B., 1910, Bearing of the Tertiary mountain belt on the origin of the earth's plan: Geological Society of America Bulletin, v. 21, p. 179–226.

Vening Meinesz, F. A., Umbgrove, J. H. F., and Kuenen, Ph.H., 1934, Gravity Expeditions at Sea 1923–32, v. II: Delft, Publication of the Netherlands Geodetic Commission, 208 p.

Walcott, C. D., 1891, Correlation papers; Cambrian, U. S. Geological Survey Bulletin 81, 441 p.

Wegener, A., 1929, Die Entstehung der Kontinente und Ozeane (4th ed.): Braunschweig, Friedrich Vieweg & Sohn, 231 p. (1966 English translation by Biram, J.: Dover Press, 246 p.).

Williams, H. S., 1894, The distribution of ancient volcanic rocks along the eastern border of North America: Journal of Geology, v. 2, p. 1–31 and one plate.

——— 1895, Memorial of James Dwight Dana: Geological Society of America Bulletin, v. 7, p. 461–479.

——— 1897, On the southern Devonian formations: American Journal of Science, 4th series, v. 3, p. 393–403.