ART. XLVI.—*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;* by JAMES D. DANA.

PART I.

PREPARATORY to a discussion of some questions connected with the earth's contraction, I here present a statement of the views which I have entertained with regard to the prominent results of this agency. They first appeared in 1846 and 1847, in volumes ii, iii and iv of the second series of this Journal, and were somewhat extended in 1856, in vol. xxii.* Full credit is given to earlier writers in connection with the articles referred to. The views are as follows:†—

1. The defining of the continental and oceanic areas began with the commencement of the earth's solidification at surface, as proved by the system of progress afterward.

2. The continental areas are the areas of least contraction, and the oceanic basins those of greatest, the former having earliest had a solid crust. After the continental part was thus stiffened, and rendered comparatively unyielding, the oceanic part went on cooling, solidifying, and contracting throughout; consequently it became depressed, with the sides of the depression somewhat abrupt. The formation of the oceanic basins and continental areas was thus due to "unequal radial contraction." ‡

* Volume ii, 385; iii, 94, 176, 380: iv, 88; xxii, 305, 335.

† I may add in this place that a sight of Mädler's chart of the Moon in 1846, six years after my visit to the crater of Kilauea, in the Wilkes Exploring Expedition, prompted to the first of the articles on the subject—that on the Volcanoes of the Moon (II. ii, 335, 1846)—in which the origin of continents and oceanic basins is considered. The most important of Prevost's papers, on the origin of mountains had been published six years before, but I knew nothing of his views until after my paper was ready for publication, as I remark in a paragraph near its close.

‡ The principle thus expressed by Prof. LeConte in volume iv of this Journal, (1872,) does not differ essentially from my old view, except that it is connected with the idea of a solid globe. Prof. LeConte, on p. 466 of his article, attributes to me the opinion that the "sinking of sea bottoms, determined by interior contraction, is the [source of the] force by which continents are elevated." But I have never referred the origin of continents to such a cause, or to any other than that stated above.

Moreover, the elevation of mountains on the borders of continents I have attributed, not to "sinking sea-bottoms" merely, but to lateral pressure produced by contraction over continental as well as oceanic areas, that on the oceanic being made much the greatest, as stated beyond. My language is frequently ambiguous on this last point, because I speak of the oceanic as the "subsiding" areas. But the term is used relatively. In volume iii, on p. 179, (1847,) I observe that mountain elevations, occur "near the limit between the great contracting and the non-contracting (comparatively non-contracting) areas:" and in various places I describe the contraction as general. In my Manual of Geology, on page 732, I remark that the elevating "force acted most strongly from the oceanic direction," which was the idea throughout. I do not deny, however, that I have supposed too

3. The principal mountain chains are portions of the earth's crust which have been pushed up, and often crumpled or plicated, by the lateral pressure resulting from the earth's contraction.

4. (*a*) Owing to the lateral pressure* from contraction over both the continental and oceanic areas, and to the fact that the latter are the regions of greatest contraction and subsidence, and that their sides pushed, like the ends of an arch, against the borders of the continents, therefore, along these borders, within 300 to 1000 miles of the coast, a continent experienced its profoundest oscillations of level, had accumulated its thickest deposits of rocks, underwent the most numerous uplifts, fractures and plications, had raised its highest and longest mountain chains, and became the scene of the most extensive metamorphic operations, and the most abundant outflows of liquid rock.

And (*b*) since the most numerous and closest plications, the great est ranges of volcanoes, the largest regions of igneous eruption and metamorphic action, exist on the *oceanic slope* of the border mountain chains, instead of the continental, therefore the lateral pressure acted most effectively in a direction *from* the ocean.

(*c*) Since these border features are vastly grander along that border of a continent which faces the largest ocean, therefore, the lateral pressure against the sides of a continent was most effective on the border of the largest oceanic basin, and for the two, the Pacific and Atlantic, was approximately proportioned to the extent of the basins; this being due to the fact that the oceanic were the subsiding areas, that is, those which contracted most, and that the larger area became the most depressed.

5. The oscillations of level that have taken place over the interior of North America, through the geological ages, have in some degree conformed in direction of axis to those of the border regions, all being parts fundamentally of two systems of movements, one dominantly in a direction northwestward or from the Atlantic, the other northeastward or from the Pacific.

6. Owing to the approximate uniformity of direction in the lateral thrust under these two systems through the successive ages, (a consequence of the isolated position of the continent between two oceanic basins, transverse to one another in axial direc-

large a part of the lateral force to have come from the special contraction and consequent subsidence of the oceanic part of the globe.

Professor N. S. Shaler in 1866 (Proc. Boston N. H. Soc., x, 237, xi, 8, and Geol. Mag., v, 511) presented, *as original*, the idea that "mountain chains are only folds of the outer portion of the crust caused by the contraction of the lower regions of the outer shell;" and that "the subsidence of ocean floors would, by producing fractions and dislocations along shore lines, tend to originate mountain chains along sea-borders and approximately parallel to them;" which is essentially the view that LeConte attributes to me. These ideas are coupled with others respecting limitations of the action of contraction due to denudation and deposition, in which I have no share.

* In my papers in 1847 I used the terms lateral pressure, lateral force, tension, horizontal force, force acting tangentially, as synonyms. "Lateral pressure" was the term oftenest employed, and it was explained by reference to a Prince Rupert's drop. (See this Journ., II, iii, 96, etc.) The action appealed to was not in any way different from the "tangential thrust" of Mallet.

tion,) mountains *of different ages* on the same border, or part of a border, have approximately the *same trend*, and those *of the same age* on the opposite border—Pacific and Atlantic—have in general *a different and nearly transverse trend.* Hence, " one dial plate for the mountains of the world, such as Elie de Beaumont deduced mainly from European geology, will not mark time for America." (This Journ., II, iii, 398, 1847; xxii, 346, 1856.)

7. The features of the North American continent were to a great extent defined in pre-Silurian time, the course of the Azoic, from the Great Lakes to Labrador, being that of the Appalachians, and various ridges in the Rocky Mountains foreshadowings of this great chain, and so on in many lines over the continental surface; and thus its adult characteristics were as plainly manifested in its beginnings as are those of a vertebrate in a half-developed embryo.

8. Metamorphism of regions of strata has taken place only during periods of disturbance, or when plication and faults were in progress; all metamorphic regions being regions of disturbed and generally of plicated rocks.

The heat required for alteration came up from the earth's liquid interior. (This part of the view requires modification, while the other part, I believe, remains good.)

9. The volcanoes of the continental areas are mostly confined to the sea-borders, or the oceanic slope of the border mountain chains, not because of the vicinity of salt water, but because these were the regions of greatest disturbance and fractures through lateral pressure. Volcanoes are indexes of danger, never " safety-valves."

10. Earthquakes were a result of sudden fracturings and dislocations proceeding from lateral pressure. In vol. iii, p. 181, (1847,) occurs the remark: " We see that the lateral pressure exerted would be likely to dislocate," and in the next line, " such fissurings, whether internal or external, would cause shakings of the earth (*earthquakes*) of great violence, and in all periods of the earth's history, and it might be over a hemisphere at once."

Another important subject—that of the systems in the trends of feature lines over the globe—is discussed in the articles referred to; but I pass it by for the present.

I propose to bring the above principles under consideration with reference to making such changes as may now be necessary.

I take up, first, the question as to whether oscillations of level, that is, subsidences and elevations, have been made by the lateral pressure resulting from contraction, as is assumed in my writings on the subject and those of most other authors;—and how was the lateral thrust from the direction of the oceanic areas made to differ in its results from that from the opposite direction? After which I shall pass to the subjects of metamorphism, igneous eruptions, volcanoes, the earth's interior, and the origin of oceanic basins.

1. *Have subsidences been produced by lateral pressure ?*

The theory of Professor James Hall, that the great subsidences of the globe have been made by the gravity of accumulating sediments, has been shown elsewhere* to be wholly at variance with physical law.

Another theory is presented by Prof. LeConte, in his recent paper in the last volume of this Journal, to which the reader is referred. Admitting, with Prof. Hall, that the mean thickness of the accumulations in the Appalachian region of Pennsylvania is 40,000 feet, and therefore that this is the measure of the gradual subsidence that attended their deposition, he shows that the temperature in the bottom deposits would have been, supposing the usual rate of increase downward (1° F. for 58 feet of descent), 800° F., and, at 10,000 feet, 230° F.; and he argues that hence there would have resulted below, first, "lithification and therefore increasing density, and therefore *contraction and subsidence pari passu* with the deposit;" next, or at a greater depth, "aqueo-igneous softening" or "melting," the temperature of 800° F. being "certainly sufficient to produce this result as well as metamorphism, and, during this process, the subsidence would probably continue;" and, in addition, the underlying strata on which the sediments were deposited would have participated in the aqueo-igneous fusion" and thus have added to the result.†

No other cause of the gradual subsidence than that here cited is appealed to.

Now *the whole of this contraction took place*, if any occurred, *in the underlying Archæan rocks* (Azoic, or Laurentian and Huro-

* This Journal, II, xlii, 210, 1866, III, v, 347, 1873; LeConte, ib., III, iv, 461, 1872.

† The principal points in Prof. Hall's theory of mountains, published in 1859, (see p. 347, of this volume,) are:

1. Coast regions the courses of marine currents, and hence of deposited sediments.
2. The accumulation of sediments by their gravity gradually sink the crust, and thus a great thickness is attained; the rocks become solidified and sometimes crystallized below.
3. The continents afterward somehow raised—not the mountain regions separately.
4. Shaping of the mountains out of other sediments by denudation.
5. Metamorphism due to "motion," "fermentation," and a little heat; the heat coming up from below (the isogeothermal planes rising) in consequence of the increasing accumulations at surface.

In Prof. LeConte's theory (this Journ., III, iv, 345, 460, 1872):

1. The same as in Prof. Hall's.
2. As explained in the text above.
3. After an aqueo-igneous softening of the beds below, the lateral thrust from the earth's contraction pressed together the region of sedimentary accumulation, plicating and crushing the beds.
4. The elevation of mountains due solely to crushing and plication.
5. Metamorphism consequent on the heating derived by the rise of the isogeothermal planes.

nian); for in obtaining by measurement this thickness, 40,000 feet, the *contracted* rocks were measured.

The 40,000 feet of subsidence required was therefore wholly independent of contraction in the stratified sediments. But these underlying Archæan rocks were probably crystallized before the Paleozoic era began; for in New York and New Jersey they are in this condition, and they underlie the Silurian rocks unconformably; and the New Jersey Archæan or Highland region is but a northern part of that of Pennsylvania and Virginia. They would consequently have expanded with the heat instead of contracting. Even if not crystallized, they would have been well compacted under the enormous weight of 40,000 feet of strata, and no experiments on rocks that I have met with authorize the assumption that the ordinary law of expansion from heat would have been set aside.

For further argument on this point I refer to the subsidence in the Connecticut valley during the era of the Connecticut River sandstone (supposed to be Triassico-Jurassic). The thickness of rock produced in the era was probably about 4,000 feet, and this is the extent therefore of the registered subsidence. The sandstone strata, as is apparent in many places, rests on the upturned metamorphic rocks—gneiss, mica schist, etc.,—of Paleozoic or earlier age. As shown in the preceding paragraph, the contraction, under Prof. LeConte's principle, must have been confined to the underlying rocks; and since these are crystalline metamorphic schists, and the depth of sandstone was not sufficient to raise much the temperature within them (the rocks are in general little compacted and often feebly solidified), the heat ascending from below as accumulation went on above would have produced expansion instead of contraction.

Without further reference to facts, it is, I think, clear that the subsidence required could not be obtained by the method appealed to by Prof. LeConte. Whatever cause, in either of the above cases, occasioned the subsidence, it must have been one that could do its work in spite of opposition on the part of the heat in the rocks themselves or those below.

Another cause of local subsidence is local cooling beneath, accompanying the increasing accumulation of sediments. But this idea is too obviously absurd to require remark.

In the present state of science, then, no adequate cause of subsidence has been suggested apart from the old one of lateral pressure in the contracting material of the globe.

2. *Have elevations been produced directly by lateral pressure?*

The theory of Prof. Hall denies that mountains are a result of *local* elevations, or of any elevation apart from a general continental. This hypothesis I have elsewhere discussed.*

* This Journal, II, xlii, 205, 252, and this volume, p. 347.

Prof. LeConte makes the elevation of mountains real, but, after explaining that the crushing effects of lateral thrust would necessarily cause a lengthening upward of the compressed strata (as in the compression of slate rocks attending the production of slaty cleavage), and thereby produce a large amount of actual elevation, arrives at the view, that there is no permanent elevation beyond what results from crushing. With crushing, in this action, plication is associated; but it should have a larger place than his words seem to give it (in all plication the rocks over a region being pressed into a narrower space, which could be done only by adding to the height), as it has performed ten-fold more work of this kind than crushing.

But are plication and crushing the only methods of producing, under lateral pressure, the actual elevations of mountain regions? Is there not real elevation besides?

In the later part of the Post-tertiary or Quaternary era, the region about Montreal was raised nearly 500 feet, as shown by the existence of sea-beaches at that height; and similiar evidence proves that the region about Lake Champlain was raised at the same time at least 300 feet, and the coast of Maine 150 to 200 feet. Hence the region raised was large. No crushing or plication of the upper rocks occurred, and none in the under rocks could well have taken place without exhibitions at surface; and this cause, therefore, cannot account for the elevation. The elevated sea-border deposits of the region are in general horizontal. This example is to the point as much as if a mountain had been made by the elevation.

But we have another example on a mountain scale, and one of many. Fossiliferous beds over the higher regions of the Rocky mountains are unquestioned evidence that a large part of this chain has been raised 8,000 to 10,000 feet above the ocean level since the Cretaceous era.* The Cretaceous rocks, to which these fossiliferous beds belong, were upturned in the course of the slowly progressing elevation, and so also were part of the Tertiary beds—for the elevation went forward through the larger part, or all, of the Tertiary era. But the local crushing or plication of these beds cannot account for the elevation, and no other crushing among the surface rocks of the mountains can be referred to this era. There may have been a crushing and crumpling of the nether rocks of the mountain. But it must also be admitted that there might have been, under tangential pressure, a bending of the strata without crushing,

* The height of the Cretaceous (stratum No. 2 of the Upper Missouri Cretaceous) at Aspen, in Wyoming, is full 8,000 feet above tide level (Meek). Beds occur also in South Park, Colorado, the height of which is 8500 feet; and, according to Hayden, in the region of the Wind River Mountains, the beds have a height of 10,000 to 11,000 feet above the sea.

especially if there is beneath the earth's rind along the continental borders a region or layer of "aqueo-igneous fusion," such as Prof. LeConte recognizes.

In the course of the geological history of the North American continent, there were many oscillations of level in the land. Portions that were raised above the sea-level in one era in another subsided again and sunk beneath it; and Prof. LeConte, in the course of his discussion, admits the existence of an elevated region along the Atlantic border which afterward disappeared. Had the elevation in the case of such oscillations been dependent on plication and crushing beneath, so complete a disappearance afterward would have been very improbable.

Such facts as the above appear to prove that elevatory movements have often been, like those of subsidence, among the direct results of lateral pressure. The facts are so well known and the demonstration so generally accepted as complete, that I have suspected that there is here an unintentional omission or oversight in Prof. LeConte's paper.

3. *Kinds and Structure of Mountains.*

While mountains and mountain chains all over the world, and low lands, also, have undergone uplifts, in the course of their long history, that are not explained on the idea that all mountain elevating is simply what may come from plication or crushing, the *component parts* of mountain chains, or those simple mountains or mountain ranges that are *the product of one process of making*—may have received, *at the time of their original making*, no elevation beyond that resulting from plication.

This leads us to a grand distinction in orography, hitherto neglected, which is fundamental and of the highest interest in dynamical geology; a distinction between—

1. A simple or *individual* mountain mass or range, which is the result of *one process of making*, like an individual in any process of evolution, and which may be distinguished as a *monogenetic* range, being *one in genesis;* and

2. A composite or *polygenetic* range or chain, made up of two or more monogenetic ranges combined.

The Appalachian chain—the mountain region along the Atlantic border of North America—is a *polygenetic* chain; it consists, like the Rocky and other mountain chains, of several *monogenetic* ranges, the more important of which are: 1. The Highland range (including the Blue Ridge or parts of it, and the Adirondacks also, if these belong to the same process of making) pre-Silurian in formation; 2. The Green Mountain range, in western New England and eastern New York, completed essentially after the Lower Silurian era or during its closing period; 3. The Alleghany range, extending from southern New York southwestward to Alabama, and completed immediately after the Carboniferous age.

The making of the Alleghany range was carried forward at first through a long-continued subsidence—a *geosynclinal** (not a *true* synclinal, since the rocks of the bending crust may have had in them many true or simple synclinals as well as anticlinals), and a consequent accumulation of sediments, which occupied the whole of Paleozoic time; and it was completed, finally, in great breakings, faultings and foldings or plications of the strata, along with other results of disturbance. The folds are in several parallel lines, and rise in succession along the chain, one and another dying out after a course each of 10 to 150 miles; and some of them, if the position of the parts which remain after long denudation be taken as evidence, must have had, it has been stated, an altitude of many thousand feet; and there were also faultings of 8,000 to 10,000 feet, or, according to Lesley, of 20,000 feet.† This is one example of a *monogenetic* range.

The Green Mountains are another example in which the history was of the same kind: first, a slow subsidence or geosynclinal, carried forward in this case during the Lower Silurian era or the larger part of it; and, accompanying it, the deposition of sediments to a thickness equal to the depth of the subsidence; finally, as a result of the subsidence and as the climax in the effects of the pressure producing it, an epoch of plication, crushing, etc. between the sides of the trough.

In the Alleghany range the effects of heat were mostly confined to solidification; the reddening of such sandstones and shaly sandstones as contained a little iron in some form;‡ the coking of the mineral coal; and probably, on the western outskirts where the movements were small, the distillation of mineral oil, through the heating of shales or limestones containing carbohydrogen material, and its condensation in cavities among overlying strata; with also some metamorphism to the eastward; while in the making of the Green Mountains, there was metamorphism over the eastern, middle, and southern portions, and imperfect metamorphism over most of the western side to almost none in some western parts.

Another example is offered by the Triassico-Jurassic region of the Connecticut valley. The process included the same stages in kind as in the preceding cases. It began in a geosyn-

* From the Greek γῆ, *earth*, and *synclinal*, it being a bend in the earth's crust.

† See an admirable paper on these mountains by Professors W. B. and H. D. Rogers, in the Trans. Assoc. Amer. Geol. and Nat., 1840–42. J. P. Lesley gives other facts in his "Manual of Coal and its Topography," and in many memoirs in the Proceedings of the American Philosophical Society. A brief account is contained in the author's Manual of Geology.

‡ Oxide of iron produced by a wet process at a temperature even as low as 212° F. is the red oxide Fe_2O_3, or at least has a red powder. (Am. Jour. Sci., II, xliv, 292.)

clinal of probably 4,000 feet, this much being registered by the thickness of the deposits; but it *stopped short of metamorphism*, the sandstones being only reddened and partially solidified; and *short of plication or crushing*, the strata being only tilted in a monoclinal manner 15° to 25°; it ended in numerous great longitudinal fractures, as a final catastrophe from the subsidence, out of which issued the trap (dolerite) that now makes Mt. Holyoke, Mt. Tom, and many other ridges along a range of 100 miles.*

These examples exhibit the characteristics of a large class of mountain masses or ranges. A geosynclinal accompanied by sedimentary depositions, and ending in a catastrophe of plications and solidification, are the essential steps, while metamorphism and igneous ejections are incidental results. The process is one that produces final stability in the mass and its annexation generally to the more stable part of the continent, though not stable against future oscillations of level *of wider range*, nor against denudation.

It is apparent that in such a process of formation elevation by direct uplift of the underlying crust has no necessary place. The attending plications may make elevations on a vast scale and so also may the shoves upward along the lines of fracture, and crushing may sometimes add to the effect; but elevation from an upward movement of the downward bent crust is only an incidental concomitant, if it occur at all.

We perceive thus where the truth lies in Professor LeConte's important principle. It should have in view alone *monogenetic* mountains and these only *at the time of their making*. It will then read, plication and shovings along fractures being made more prominent than crushing:

Plication, shoving along fractures and crushing are the true sources of the elevation that takes place *during the making* of geosynclinal monogenetic mountains.

And the statement of Professor Hall may be made right if we recognize the same distinction, and, also, reverse the order and causal relation of the two events, accumulation and subsidence; and so make it read:

Regions of monogenetic mountains were, previous, and preparatory, to the making of the mountains, areas each of a slowly progressing geosynclinal, and, *consequently*, of thick accumulations of sediments.

The prominence and importance in orography of the mountain individualities described above as originating through a

* This history is precisely that which I have given in my Manual of Geology, though without recognizing the parallelism in stages with the history of the Alleghanies.

geosynclinal make it desirable that they should have a distinctive name; and I therefore propose to call a mountain range of this kind a *synclinorium*, from *synclinal* and the Greek *ὄρος*, *mountain.*

This brings us to another important distinction in orographic geology — that of a second kind of monogenetic mountain. The *synclinoria* were *made through a progressing geosynclinal.* Those of the second kind, here referred to, were *produced by a progressing geanticlinal.* They are simply the upward bendings in the oscillations of the earth's crust—the geanticlinal waves, and hardly require a special name. Yet, if one is desired, the term *anticlinorium*, the correlate of *synclinorium*, would be appropriate. Many of them have disappeared in the course of the oscillations; and yet, some may have been for a time—perhaps millions of years—respectable mountains. The "Cincinnati uplift," extending southwestward from southern Ohio (about Cincinnati) into Tennessee, and referred by Newberry and others to the close of the Lower Silurian, was made at the same time, or nearly, with the Green Mountains; but, while the latter range is a synclinorium, the former is a geanticlinal or an anticlinorium, and it is one of the few (probably few) permanent monogenetic elevations of this kind over the earth's surface. There may possibly have been crumpling or crushing in the deep-seated rocks below which determined its permanence. As far as the Paleozoic rocks constituting it go, it is a *simple* synclinal; but it is really a synclinal of the earth's crust, and hence wholly distinct from ordinary synclinals, or those subordinate among the plications in a synclinorium, like the synclinals of the Alleghanies.

The geosynclinal ranges or synclinoria have experienced in almost all cases, since their completion, true elevation through great geanticlinal movements, but movements that embraced a wider range of crust than that concerned in the preceding geosynclinal movements, indeed a range of crust that comes strictly under the designation of a polygenetic mass. Thus the Connecticut valley sandstone beds, which must have been but little raised by the slight upturning they underwent at the epoch of their disturbance (since there was then neither plication nor crushing) are now seven hundred feet higher above the sea-level in Massachusetts than near New Haven, Conn.; and this is owing, not to denudation but to a subsequent elevation in which much of New England participated—a true geanticlinal uplift. So it has been the world over. The great uplift of the Rocky Mountain region of more than 8,000 feet, which began after the Cretaceous, had nothing to do, as I have said, with crushing or plication, although there was disturbance of the beds in certain local Cretaceous and Tertiary areas; it appears to have been a true geanticlinal elevation of the Rocky Mountain mass, itself mainly, if not wholly, a combination of synclinoria.

Geosynclinals and geanticlinals of low angle, like those of the present day, graduate insensibly into horizontal surfaces. The later oscillations in the world's history have taken in a vastly wider range of crust than those of early time. We cannot point to any geosynclinal in progress that is probably on the way to become the site of a new synclinorium. This comes from the fact already stated, that 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; and the further fact that this process has been often repeated in past time, until the crust has been so stiffened above, as well as below, that only feeble flexures of vast span are possible, even if the lateral pressure from contraction had not also declined in force.

4. *How was the lateral thrust from the direction of the ocean made to differ in its action or results from that from the opposite direction?*

The fact of a difference in the effects of the lateral thrust from the opposite directions, the oceanic and continental, is beyond question. The evidence may here be repeated.

The greatest of elevations as well as subsidences, and also of plications and igneous eruptions, have taken place on the continental borders or in their vicinity; they thus show that there is something peculiar along such regions. Again, the border mountains in North America are parallel to the axes of the adjoining oceans; and thereby at right angles, instead of parallel to one another. Again, the folds in the Appalachians are not symmetrical folds, but, instead, have one slope much steeper than the other, proving inequality in the action of lateral pressure from the continental and oceanic directions. Further, the larger ranges of uplifts and effects of heat occur on the *oceanic* slope of the principal border-mountain chain, instead of the continental slope, favoring the view that this lateral thrust was more effective in the direction from the ocean against the continents than in the opposite. Finally, there is the fact that the disturbances or effects of lateral thrust have been *very much the greatest* on the border of the *largest* oceans.

But has this greater effectiveness of lateral thrust from the direction of the ocean been due to a proportionally greater contraction and subsidence of the oceanic crust than the continental —the sinking causing the oceanic arch to press against the sides of the basin. I formerly made this the chief means of mountain lifting; and now, while not giving it so great prominence, I believe it to be a true cause. It is certain that the depressing of the ocean's bed, like the raising of the continental areas, has been in progress through the ages. The great principal rise of the continent and continental mountains took place after the Cretaceous period or during the Tertiary, and some of it even in the Quaternary; and this is almost positive demonstration that the bottoms of the oceans were tending downward cotemporaneously. It is not possible in the nature of contraction that it should have been all accomplished in these basins at the beginning of their existence—a point I shall further illustrate when discussing the nature of the earth's interior. Moreover, the mobile waters that occupy the oceanic depressions would have given important aid in the cooling of the underlying crust. It is to be noted, also, that the distance between the axis of the Appalachians in North America, and the opposite (African) side of the Atlantic is 4000 miles; and that between the axis of the Rocky Mountains and the opposite (Australian) coast of the Pacific is over 7000 miles, while between the axis of the Appalachians in Virginia and that of the Rocky Mountains in the same latitude, the distance is hardly 1500 miles. Hence the contraction was absolutely greatest over the oceanic areas, independently of any result from special causes; and if the generated pressure were not expended in uplifts over the oceanic areas themselves, it would have been in uplifts on its borders.

In addition to the above advantage which the oceanic areas have had in the making of border oscillations, the lower position of the oceanic crust, and the abruptness with which the sides fall off, give it an opportunity to push beneath the sides of the continents, and this would determine the production of such mountains and just such other effects of pressure, on the continental borders, as actually exist, even if contraction were equable over the globe, that is, were alike in rate over the oceanic and continental areas. It puts the oscillations over the continents inevitably under the direction of the adjoining oceanic crust. The angle of slope of the deepwater sides of the oceanic basin is generally above five degrees.*

* The angle of slope on the sides of the Oceanic basin has not yet been properly investigated. The margin of the basin on the Atlantic border is now in about 100 fathoms water (600 feet). According to soundings by the Coast Survey, as I am informed by Mr. A. Lidenkohl of the Coast Survey Office, through J. E. Hilgard, Esq., Assistant-in-Charge, the slope between 100 and 200 fathoms off Cape Hatteras is 2° 31′; off New York entrance, 2° 02′; off George's Shoal, 1° 35′. But for the region beyond 200 fathoms, the data are not sufficient for any certain conclusion. Mr. Lidenkohl observes: "If the soundings by Lieut. Murray off Cape Lookout can be trusted, the slope between the 100 and 2000 fathom line must be over 7 degrees. Berryman's soundings off St. George's Bank indicate a slope of about 3½ degrees. From this it may be inferred that the slope rather increases than decreases beyond the 200 fathom line."

This conclusion is further sustained by the known universality of oscillations over the oceanic basin. The central Pacific area of coral islands—"registers of subsidence"—stretches from the eastern Paumotus to the western Carolines, ninety degrees in longitude; and it indicates that the comparatively recent coral-island subsidence involved a region stretching over more than one-fourth the circumference of the globe. The fact teaches that the movements of the globe, which have been in progress through all time in obedience to the irresistible energy generated by contraction, have been world-wide, and so world-developing, even down to the latest era of geological history.

The above considerations sustain me in the opinion expressed in 1856 (this Journal, xxii, 335), that the relation in size between the mountains and the bordering oceans is not merely "formal," as pronounced by my friend Prof. LeConte, but has a *dynamical* significance.

In view of the considerations here presented, I believe there is no occasion to reject the fourth proposition (4 *a*) on page 424; but only to modify it as follows:

4*a*. Owing to the general contraction of the globe, the greater size of the oceanic than the continental areas, and the greater subsidence from continued contraction over the former than over the latter, and also to the fact that the oceanic crust had the advantage of *leverage*, or, more strictly, of obliquely upward thrust against the borders of the continents, because of its lower position, *therefore*, these borders within 300 to 1,000 miles of the coast, etc.

5. *Mountain-making slow work.*

To obtain an adequate idea of the way in which lateral pressure has worked, it is necessary to remember that mountain elevaion has taken place after immensely long periods of quiet and gentle oscillations. After the beginning of the Primordial, the first period of disturbance in North America of special note was that at the close of the Lower Silurian, in which the Green Mountains were finished; and if time from the beginning of the Silurian to the present included only fifty millions of years—which most geologists of the present day would consider much too small an estimate—the interval between the beginning of the Primordial and the uplifts and metamorphism of the Green Mountains, was at least ten millions of years. The next epoch of great disturbance in the same Appalachian region was that at the close of the Carboniferous era, in which the Alleghanies were folded up: by the above estimate of the length of time, thirty-five millions of years* after the commencement of the Silurian; so that the Appalachians were at least 35,000,000 of years in making, the preparatory subsidence having begun

* These estimates of the relative lengths of ages are based on the maximum thickness of their rocks—very uncertain data, but the best we have.

as early as the beginning of the Silurian. The next on the Atlantic border was that of the displacements of the Connecticut River Sandstone, and the accompanying igneous ejections, which occurred before the Cretaceous era:—at least seven millions of years, on the above estimate of the length of time, after the Appalachian revolution. Thus the lateral pressure resulting from the earth's contraction required an exceedingly long era in order to accumulate force sufficiently to produce a general yielding and plication or displacement of the beds, and start off a new range of prominent elevations over the earth's crust.

6. *System in the mountain-making movements on the opposite borders of the North American Continent, and over the Oceanic areas.*

A summary of the general system of movements and mountain-making on the opposite borders of the continent, and over the oceanic areas, will, I think, render it apparent that the views here sustained have a broad foundation.

I omit any special reference to the Archæan elevations, and also the local disturbances in the Primordial of Newfoundland, as well as the facts relating to minor changes of level.

A. Mountain-making on the Atlantic border.

(1.) At the close of the Lower Silurian, or a little earlier, a culmination of the great Appalachian geosynclinal resulted in displacements, plications and metamorphism, and the making of a *synclinorium*, along the *Green Mountain* region—these mountains (some summits at present over 4,000 feet high above the sea) being the result. The depth to which the region subsided during the Lower Silurian era, and the thickness of the accumulations, are not ascertained; probably the extent was not less than 20,000 feet.

(2.) Simultaneously, a *permanent anticlinorium* was made over the Cincinnati region, from Lake Erie into Tennessee, parallel with the Alleghanies of Virginia, 250 miles to the northwest.

(3.) The Acadian region—embracing western Newfoundland, St. Lawrence Bay, the Bay of Fundy, and part of Nova Scotia and New Brunswick adjoining, and probably the sea southwest between St. George's Bank and the coast of Maine, with also an area in Rhode Island—was the course of a great geosynclinal, or a series of them, parallel in general direction with that of the Appalachian region; it continued in progress, but with mountain-making interruptions, and some shift of position to the eastward, from the Silurian to the close of the Jurassic.

At the close of the Lower Silurian, no general disturbances occurred in this Acadian region, so far as is known. In the Anticosti seas, or northern part of St. Lawrence Bay, limestones, as Logan states, were uninterruptedly in formation from the beginning of the Hudson period of the Lower Silurian to the middle of the Upper Silurian, showing that the Acadian geosynclinal was then in regular progress. It so continued until—

The close of the Devonian, when disturbances, plication and metamorphism took place in eastern Canada, Nova Scotia and the bordering region of New Brunswick, and the most extensive of Acadian Paleozoic synclinoria resulted, according to the observations of Dr. Dawson and others.

(4.) The close of the Carboniferous age was an epoch of mountain-making in the Allegheny region, the Alleghanies from New York to Alabama having been then made, as already explained.

(5.) At the same time there were disturbances and synclinorian plications in the Acadian region. During the Carboniferous era, according to Logan and Dawson, 16,000 feet of rock had in some parts accumulated, and therefore a geosynclinal of 16,000 feet formed, the rocks in their many coal-beds and root-bearing layers bearing evidence, to the last, of oscillations involving an intermittent but progressing subsidence. The synclinorium, the resultant, was much less marked than that at the close of the Devonian.

(6.) During the Paleozoic, along the sea-border, a more or less perfect barrier was made by a geanticlinal uplift (anticlinorian), which was a counterpart to the geosynclinal of the Appalachian region. (See beyond.)*

(7.) The middle or close of the Jurassic period was an epoch of displacements, and the making of a series of imperfect synclinoria along the Triassico-Jurassic areas from Nova Scotia to Southern North Carolina, as sufficiently described.

(8.) During the era of the Connecticut River sandstone (Triassico-Jurassic) a nearly complete sea-border anticlinorium existed—a counterpart to the progressing geosynclinal. Its existence is proved by the absence of all marine fossils from the beds.*

(9.) The era closing the Cretaceous, and that of the Tertiary, witnessed but small uplifting and some local displacements of the rocks of these eras on the Atlantic border. The principal movement was geanticlinal, and it involved probably the whole Alleghany region.

(10.) In the Quaternary there were extended movements of geanticlinal and geosynclinal character which need not be here described.

* In my Manual of Geology, the probable existence of such a barrier is recognized in connection with the remarks on the geography of the Trenton period in America; and it is particularly dwelt upon, and illustrated by a map, in the chapter on the Triassic; but it is not spoken of as connected in origin with the geosynclinal that was in progress to the west of it. Evidence with regard to this anticlinorium is given in the following part of this memoir.

B. Mountain-making after Archæan time on the Pacific border, within the territory of the United States.

(1.) At the close of the Lower Silurian, none yet known.

(2.) At the close of the Devonian, none yet known.

(3.) At the close of the Carboniferous age, or the Paleozoic, none yet known; and if none really occurred, then the contracting globe at that time, as far as U. S. N. America is concerned, must have expended its energies, which it had been gathering during the Paleozoic, in making the Alleghanies and in some minor plications along the Acadian region

The "Great Basin," between the Sierra Nevada on its western border, and the Wahsatch range on its eastern (lying along the meridian just east of the Great Salt Lake), contains a number of short ridges, parallel to these lofty border ranges, some of which are quite high;* and they consist, according to King, "of folds of the infra-Jurassic rocks"; and "it is common to find no rocks higher than the Carboniferous," owing, it is stated, to the erosion that has taken place. It is not clear that part, at least, of the Great Basin plications may not have taken place before the Jurassic era. If not, then the movements must have been in some way involved with those of the Sierra and Wahsatch regions.

(4.) At the close of the Jurassic, two great geosynclinals, which had been in progress through the Paleozoic and until this epoch in the Mesozoic, culminated each in the making of a lofty synclinorium—one, the Sierra Nevada, some of whose summits are over 14,000 feet high; the other the high Wahsatch, a parallel north and south range.

Whitney has proved that the Carboniferous and Jurassic rocks are comformable in the Sierra Nevada range, and that the close of the Jurassic was the epoch of its origin; but direct proof is not yet found that the Devonian and Silurian formations are included. The granite axis of the chain probably indicates, as LeConte has suggested, the region of maximum disturbance and metamorphism.

The Wahsatch contains, according to Clarence King, formations of all the ages from the Lower Silurian to the Jurassic, and the whole are throughout conformable; and a great thickness of crystalline rocks exists beneath, supposed to be Archæan, which he states are conformable also. The plications and mountain-making took place, as King states, cotemporane-

* An admirable chart, giving in detail the topography of this whole region, and including the Wahsatch, has been prepared by Mr. James T. Gardner after careful surveys by himself, topographical surveyor of the Exploration of the Fortieth Parallel under Clarence King, and is now ready for the engraver. Mr. King has published thus far only brief chapters on the geological results of his survey, in the volume of J. T. Hague on Mining Industry (vol. III). He has ready for publication Vols. I and II, on Systematic and Descriptive Geology. The Botanical Report of the Survey, Vol. V, has been issued; but Vol. IV, on Zoölogy and Paleontology, remains to be completed.

ously with the same in the case of the Sierra, before the Cretaceous era, the Cretaceous beds lying on the Jurassic unconformably.

These two synclinoria are 400 miles apart. The preparatory geosynclinal of the Wahsatch—and probably that of the Sierra—took for its completion, supposing it to have begun with the opening Silurian, a period at least a fifth longer than the whole Paleozoic.

(5.) At the close of the Cretaceous, another pair of geosynclinals, parallel with the coast, but geosynclinals of only Cretaceous origin, culminated in synclinoria.

One of the Cretaceous geosynclinals was in progress *east of the Wahsatch*, along the whole summit region of the Rocky Mountains, in the United States. Directly east of the Wahsatch, according to King, the beds are 9,000 feet or more thick; and, as Hayden states, they have a great thickness in the Laramie Plains, and little less over the upper Missouri region; so that the downward movement was in some parts a profound one, and affected a very wide extent of country. Hayden and King make this disturbance to have taken place after part, or all, of the Eocene period had passed, while Prof. Marsh holds that it occurred at the close of the Cretaceous period.*

* Clarence King has very briefly described the Wahsatch region, as well as the country to the west, in the third volume (4to, 1870) of his United States Geological Exploration of the 40th parallel; and on page 454, he says: "Subsequent to the laying down of the old Cretaceous system, and of those conformable freshwater beds which close the coal-bearing period, another era of mountain uplifts occurred, folding the coal series [Cretaceous and Lower Tertiary] into broad undulating ridges having a general trend of northeast." He then observes that freshwater Tertiary beds of sand and clay, "an immense accumulation," were laid down *unconformably* over this upturned Cretaceous, and, after the Miocene era, were subjected to "orographic" disturbance and "tilted to an angle of 15° to 20°, or thrown into broad and gentle undulations wherever they lie in the neighborhood of the older ranges such as the Wahsatch and Uintah." These disturbances were confined to within 15 miles of the Wahsatch. The period in which they occurred witnessed also great outflows of trachytic rocks in this and other parts of the Rocky Mountain region. Mr. King adds, on page 455, that there is no question as to the identity of the beds that *overlie unconformably* the Cretaceous folds along the eastern flank of the Wahsatch with the horizontal Tertiary deposits of the Green River Basin; and that over this basin between the Green River and the Wahsatch, no single instance of conformity occurs between the coal beds and the overlying horizontal freshwater strata. As stated above, he makes the epoch of Cretaceous uplifting to have followed, not the Cretaceous period, but the earliest period of the Tertiary, Eocene beds being, in his view, included with the Cretaceous in the folds referred to.

Dr. Hayden has investigated with much detail the Green River Basin and the region east of it, and years since announced that the Lower Tertiary beds, in some parts of the Rocky Mountain region, were tilted at a high angle. He has held that all the Coal-bearing strata were Lower Tertiary; but now agrees with the view expressed by King, and first suggested by Meek, that part are Cretaceous, while another part are Lower Tertiary, and considers the later Tertiary beds, which lie unconformably on the beds below in the regions of disturbance, Miocene and Pliocene. He states that the thickness of the Cretaceous formation in the Laramie Plains is 8,000 to 10,000 feet. He observes in a recent letter to the writer that the Coal-bearing strata and Cretaceous are never unconformable; but

The other geosynclinal belt of the Cretaceous era was to the *west of the Sierra Nevada*, as described by Whitney. This coast geosynclinal ended in extensive displacements and plications, much metamorphism, and a high synclinorium.

(6.) The intermediate region—the Great Basin, which had been widened at the close of the Jurassic by the annexation of the plicated and consolidated Sierra and Wahsatch—was the area of a geanticlinal, or at least of absence of subsidence; for King says no Cretaceous rocks occur over it.

(7). With the close of the Cretaceous, or when the Cretaceous synclinorian movements of the sea-coast and mountains were ending, a geanticlinal movement of the whole Rocky Mountain region began, which put it above the sea-level, where it has since remained. This upward movement continued through the Tertiary.

(8.) During the Tertiary age, until the close, probably, of the Miocene Tertiary, another pair of parallel geosynclinals—but geosynclinals of Tertiary formation—were in progress. The Cretaceous synclinoria had given still greater breadth and stability to the relatively stable region between them, and one of these new troughs is hence farther east on the mountain side, and the other farther west on the coast side.

In the coast geosynclinal, marine Tertiary beds were accumulated to a thickness of 4000 to 5000 feet; and then followed the epoch of disturbance ending in another coast synclinorium, a coast range of mountains, in some places metamorphic, and having ridges, many of which are at present 2,000 feet or more in height above the sea, and some in the Santa Cruz Range, according to Whitney, over 3,500 feet.

The other is to the east of the Cretaceous axis in the summit region of the Rocky Mountain chain. A great thickness of freshwater beds was made in the Green River region and some other places about the Rocky Mountain summits, and thinner deposits to the eastward. The thickness, in connection with

instead are often folded together, and sometimes stand at a high angle, even vertical in many places, as in the Laramie Plains south of Fort Sanders; along the Big Horn region; between Long's Peak and Pike's Peak; near Denver in Colorado, etc. Near the mouth of the Big Horn. The Chetish or Wolf Mts. consist of these upturned strata and have a height of 1500 to 2000 feet above the Yellowstone. He found the later Tertiary beds sometimes tilted at a small angle, never over 10°.

The discovery of Dinosaurian remains in some of the Coal beds, announced by Marsh and Cope, and of *Inocerami*, as ascertained by Meek, is one part of the evidence on which the lower parts of the Coal beds is determined to be Cretaceous. Besides this, there is the fact that the supposed Miocene of the Green River Basin contains remains of mammals that are decidedly Eocene in character; and if these are Eocene, then the Coal beds are something older. Prof. Marsh is very strongly of the opinion that all the *Coal beds are Cretaceous.*

On the other side, Lesquereux states that the evidence from fossil plants is totally opposed to making any of the Coal strata Cretaceous.

The method of mountain-making, and the principle involved, are the same whatever be the decision as to the exact epoch of the Cretaceous plication.

evidences of shallow water origin, indicates a progressing geosynclinal, although the ocean gained no entrance to it. The downward bending ended probably just after the Miocene period without general displacements; but there were tiltings along the more western border of the Tertiary in the vicinity of the Wahsatch and other mountains. (See note on page 439.)

(9.) Since the Miocene era, and on through much of the Quaternary, there have been vast fissure-eruptions over the western Rocky Mountain slopes. They had great extent especially in the Snake River region where the successive outflows made a stratum 700 to 1000 feet thick, over an area 300 miles in breadth. There are other similar regions but of less area.

It is thus seen that along the Pacific side of the continent the crust, under the action of lateral pressure, first bent downward profoundly, and then yielded and suffered fracture and plications, directly along a belt, parallel with the coast, either side of the Great Basin (and perhaps over this basin to some extent), the two great lines 400 miles apart. The plicated regions, thus made, having become firm by the continued pressure and the engendered heat and resultant solidification, the crust next bent, and then yielded, in a similar way, along an axis outside of the former regions of disturbance, the two axes over 600 miles apart; and again all was mended in the same way. Then it bent a third time, just outside of the last range, on each side of the same great area, the lines over 700 miles apart; and then, over the western of the two ranges, the beds were displaced, solidified, and left in high ridges; but over the eastern the final disturbances were local and slight.

There were hence two parallel series, cotemporaneous in steps of progress, situated on opposite borders of the Great Basin, a *coast* series, and a *mountain* series, each having its highest member toward the basin; the coast series, the grandest in its three parts, and leaving evidences of the profoundest disturbance, and the greatest amount of metamorphism. The Wahsatch range is nearly as high as the Sierra; but probably a fourth of its height is due to the final elevation of the Rocky Mountain region.

The last bendings were more local than the preceding because the crust had become stiffened by its plicated and solidified, and partly crystallized, coatings, as well as by thickening beneath; and therefore, while the Tertiary movements were in progress, the part of the force not expended in producing them carried forward an upward bend, or geanticlinal, of the vast Rocky Mountain region as a whole. For the same reason, profound *breakings* took place where bending was not possible, and thereby immense floods of liquid rock were poured out over the surface. (Most of the great mountains of the globe were lifted about this time, that is, in the course of the Tertiary era, and many of the great volcanoes were made.)

There were irregularities or exceptional courses in connection with this system of movements and their effects. But these show only that in the same area the lateral pressure at work was not alike either in amount, or in direction, in different latitudes; nor was the resistance before it the same.

The results correspond with the well-understood effects of lateral pressure. Suppose a long beam, having an even texture except that a portion toward the middle (say a sixth of the whole length) is stouter than the rest, to be subjected at its extremities to direct pressure. The first yielding and fracture would take place toward the stouter portion on either side. If this break were mended by splicing and cementing until firmer than before, the next region of yielding would be just outside of the former. In brief, the fracturing would be in each case near the stouter portion of the beam. Moreover, the extent of the yielding and fracture on each side would have some relation to the amount of pressure against that side. Just so has it been with the earth's crust under the action of lateral pressure. The facts further illustrate the truth, before announced, that the force from the ocean side had in some way the advantage, and in fact was the greater. But the full difference is not indicated by the difference in the results of disturbance, since the shoving force on the side of greatest pressure would not be limited in its action to its own side, unless the intermediate stouter region were wholly immovable.

C. Movements over the Oceanic areas.

The history of the changes of level over the oceanic areas is necessarily a meager branch of geological science. There are, however, some great truths to be gathered which are of profounder import than is generally acknowledged. They show that the occeanic crust has sometimes acted in the capacity of a single area of depression, although of so immense extent. I allude briefly here to only two of the facts, referring the reader to my former articles for a fuller discussion of the subject.

First, the remarkable one that nearly all the ranges of islands over the Pacific ocean, and even the longer diameters of the particular islands, lie nearly parallel with the great mountain ranges of the Pacific coast of North America. There is a dynamical announcement in this arrangement—which is partly recognized when we refer it, as I have proposed, to the existence of directions of easiest fracture in the very nature of the infra-Archæan crust, and regard the courses of these feature lines of the oceans and continents as having reference to one of these directions. But, besides this, there is a declaration with regard to the *direction* of the pressure that acted against the continents and reacted over the oceanic areas.

The other fact is that of the Coral island subsidence, already referred to, which affected the tropical ocean for its whole breadth, or more than a quarter of the circumference of the globe; sinking the sea bottom at least 3000 feet over a large part of the area, and probably over its axial portions two or three times this amount.* The oceanic basin was evidently one basin in its movement; but the areas of less and greater subsidence, of parallel N.W. by W. trend, so alternate along the southern border of the region of subsidence that we may conclude there were great parallel waves, made by lateral pressure in the crust, as I have elsewhere explained,† that is, geosynclinals and geanticlinals, such as are the only possible conditions of the crust under the lateral pressure of contraction. Now this great oceanic subsidence, involving the breadth of the ocean, if begun in the Tertiary era, as is probable, was going forward at the very time when the Rocky Mountains, and other great mountains of the globe, were in progress of elevation, as if these were counterpart movements in the earth's surface; and it continued on during the Glacial era, when the continental elevations appear to have reached their highest limit.

We gather from these facts how it is that a general submergence, or an emergence, might characterize cotemporaneously large areas of North America and Europe; as, for example, in the Subcarboniferous, Carboniferous and Permian periods, during which the rocks show that there was a general parallelism in the movements. If a geanticlinal were in progress over the middle of the Atlantic crust, as a result of the lateral thrust in the continental and oceanic crusts, there might also be a reverse movement or general sinking along the continental borders, as well as a rise of water about the continents from the diminution in the ocean's depth; and when the oceanic geanticlinal flattened out again through subsidence, the subsiding crust would naturally produce a reverse movement along one or both continental borders.

From the various considerations here presented, derived from both the continental and oceanic areas, it is apparent that the earth has exhibited its oneness of individuality in nothing more fundamentally and completely than in the heavings of its contracting crust.

The subjects of metamorphism, the earth's interior, igneous eruptions and volcanoes remain for discussion. In addition I propose to consider the steps in the origination of the continental plateaus and oceanic basins, and also present some facts bearing on the general nature of the infra-Archæan crust, that is, the part below the earth's superficial coatings.

* Author's Rep. Geol. Wilkes U. S. Expl. Exped., 4to, 1849, p. 399; and Corals and Coral Islands, 8vo, 1872, p. 329.

† Rep. Geol. Expl. Exped., p. 399; Corals and Coral Islands, p. 328.