Art. XXX.—*On the Volcanoes of the Moon*; by James D. Dana.

(Read before the Assoc. of Amer. Geologists and Naturalists, Sept., 1846.)

The surface of the moon affords a most interesting subject for the study of the geologist. Though at a distance of many thousand miles, the telescope exhibits to us its structure with wonderful distinctness; and already, as a learned astronomer has observed, we are better acquainted with the actual heights of its mountains, than with those of our own planet.* Having an atmosphere of extreme rarity† (if any) and never obscured by clouds, its features are wholly open to view, and the eye aided with glasses, may wander over its rugged crags, survey its craters, its Alps and its Apennines, from their bases to their summits. Neither are there any sedimentary deposits, soil or vegetation,—for there can be none without water,—and the igneous surface therefore is still its own naked self, exhibiting the results of ig-

* M. Arago, Annuaire des Longitudes, pour l'an 1842, 2d ed., Paris, 1842.—P. 526, in an article on the Lunar Volcanoes, Arago says:—"Il est remarquable que grace au zèle et à l'exactitude d'Hevelius on ait connu la hauteur des montagnes de la Lune beaucoup plus tôt que la hauteur des montagnes de la Terre."

† The evidence in favor of the existence of an atmosphere and of water in the moon, hitherto obtained, has not been deemed satisfactory. Herschel, at an eclipse, Sept. 5, 1793, observed the sharp horn of the limb of the moon, and says that it seemed perfectly regular; and that a deviation of a single second by the refraction of the solar light in the moon's atmosphere would not have escaped him. *Phil. Trans.*, 1794, p. 39.—As stated in Beer and Mädler, (p. 133.) Schröter calculated the density of the supposed atmosphere to be one twenty-eighth the density of our own atmosphere; and Melanderhjelm demonstrated that the moon's atmosphere, judging from that of the earth, should have one thirty-sixth the density of our own atmosphere. But the above mentioned authors say that we have yet to prove that the moon has any atmosphere, adding that it must be very much more rare than the rarest gas on earth. They observe also that supposing our atmosphere to extend through space, its density half way to the moon, according to the Mariottian law of decrease, would be expressed by the fraction $\frac{1}{100000\ldots}$, the denominator extending to ten thousand zeros. The singular observation occasionally made, that during the passage of the moon over a star, the star appears visible in front of the edge of the moon, before disappearing, may possibly indicate an extremely low atmosphere or surface vapors: but it has been attributed with much appearance of reason (Rep. Brit. Assoc., 1845, p. 5) to diffraction.

The absence of any bodies of water on the moon is placed beyond doubt, both by actual telescopic examination and by inference from the absence of clouds. There are no streams, lakes or seas. An eminent astronomer has remarked that the heat of the surface exposed to the sun would occasion a transfer of any water the moon might contain to its dark side, and that there may be frosts in this part, and perhaps running water near the margin of the illumined portion. But in such a case, would not clouds appear about the margin at times in telescopic views?

neous action in their simple grandeur, unaltered and uncomplicated by any attending operations. We may hope therefore to find some profit in contemplating for a few moments this land of the skies: and although we may not look for very speedy "annexation," we may possibly gather some facts and ideas which the decree of Truth will annex to the domain of Science.

The moon, as we all know, has been minutely studied in a physical point of view, and already some important geological conclusions have been drawn from the facts it presents. The altitudes of its mountains were first estimated by Galileo,* and afterwards were mathematically calculated by Hevelius† and Riccioli. Sir Wm. Herschel continued the investigations, and reported the probable activity of three of its volcanic mountains.‡ Mayer, Huth, Harding, and Schröter,§ and more lately Gruithuisen and W. G. Lohrmann,‖ are other prominent names among those who have added largely to our knowledge of the moon's surface. More recently still, MM. Beer and Mädler have pursued this science of Selenography with wonderful perseverance and labor, and have given corrected results of all previous calculations, with magnificent maps of the moon's topography.¶ 1095 heights were carefully measured by them, and their features, to a great degree of accuracy, ascertained. These maps have afforded M. Elie de Beaumont some deductions alledged as supporting certain geological theories. James Nasmyth, Esq., in the Transactions of the Royal Astronomical Society for the present

* In the article referred to in the Annuaire des Longitudes, (p. 522,) Arago states that Clearchus, on the authority of Plutarch, described the moon as smooth and lustrous like a mirror. Democritus attributed the spots to inequalities of surface. Galileo first observed the lunar mountains with his telescope in 1610, and estimated their height at one twentieth of the diameter, giving 8800 metres for their altitude, which but little exceeds their actual height.

† J. Hevelius, Selenographia; fol., Gedani, 1647.

‡ *Phil. Trans. for* 1780, p. 507, Astronomical Observations relating to the Moon: —*for* 1787, p. 229, An Account of Three Volcanoes in the Moon:—*for* 1794, p. 39, Account of some particulars observed during the late Eclipse (in 1793) of the Sun.

§ J. H. Schröter, Selenotopographische Fragmente zur genauern Kenntniss der Mondfläche ihrer erlittenen Veränderungen und Atmosphäre; 2 vols, 4to, Göttingen, 1791 and 1802.—Gruithuisen, in Bode's *Astron. Jahrb.*, 1825.

‖ Topographie der sichtbaren Mondoberfläche, von W. G. Lohrmann; 4to, Dresden und Leipzig, 1824.

¶ Allgemeine vergleichende Selenographie; mit besonderer Beziehung auf die von den Verfassern herausgegebene Mappa selenographica, von W. Beer und Dr. J. G. Mädler; Berlin, 1837.

year, has published important observations on the features of the moon's mountains, and traced out their volcanic character.* A very valuable memoir on the same topics has been presented within the current year to the Institute at Paris, by M. Rozet, in which the moon is shown to have been a globe in complete fusion, which has slowly cooled; and its peculiarities are dwelt upon as an exhibition, in many respects, of the former state of our own planet.†

In all the geological observations which have been hitherto made with regard to the moon, one important feature remains unsatisfactorily explained. I refer to the vast magnitude of its craters. It is not surprising that in view of their stupendous size, many should have been incredulous as to their crater character, and preferred to designate them by some non-committal term, as circular ridges, or ring-mountains; nor that geologists in general have hardly ventured to acknowledge their belief in these lunar wonders. Imagine if possible, in place of an ordinary crater, circular areas 50 to 150 miles in diameter, and 10,000 to 20,000 feet in depth. Such are many of the lunar craters; and they are crowded in great numbers over the larger part of its surface, varying from even a more capacious magnitude, down to those that measure but a few miles in breadth. It is not astonishing that there should be found much difficulty in reconciling their features with those of Vesuvius and Etna, hitherto received too generally as the types of volcanoes and volcanic action. The crater of Kilauea in the Hawaiian Islands is of a wholly different character, and I propose to present some illustrations which it affords, appealing to such general facts regarding it as are already well known. If I mistake not, it will be found to give a full interpretation of whatever has been considered mysterious in these lunar ring-mountains. After these illustrations, we may return again to earth, and apply the knowledge which we have derived abroad, in exemplifying the former geological history of our own planet.

We may first consider the general features of the moon's surface.

About two-thirds of the lunar hemisphere in view, comprising almost the whole of the southern half and the northeast quarter,

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* *Memoirs of the Royal Astronomical Society*, vol. xv, 1846: On the Telescopic Appearance of the Moon, by James Nasmyth, Esq., p. 147.

† Sur la Selénologie, by M. Rozet, *Comptes Rendus*, 1846, xxii, 470.

are covered thickly with volcanic mountains. Over a large part of the northwest quarter, there is only here and there an elevation, and this comparative nudity extends a considerable distance southward across the equator.

The features of the surface may be distinguished as of five kinds, viz :—

1. The ring-mountains, which are broad truncated cones with immense circular craters. (See the following figures from Beer and Mädler.)

2. Conical mountains, nearly like ordinary volcanoes.

3. Linear or irregular ridges.

4. Large depressed areas, usually termed seas, but not supposed to contain water.

5. Broad pale streaks, of great length.

6. Narrow lines, supposed to be fissures.

Out of the 1095 heights measured by Beer and Mädler, *six* are above 20,000 feet in altitude, and *twenty-two* exceed 15,750 feet.

The broad truncated cones with large circular craters, are its most common elevations, and are among the loftiest. The pits, as we have remarked, are of all dimensions to 150 miles, and of various depths to near 25,000 feet. The crater *Baily* is 149½ statute miles in diameter ; *Clavius* is 143⅓ miles ; *Schickard* is 128 miles. 20 to 60 miles is the more common breadth. The depth of *Newton* is 23,833 English feet ; of *Casatus* 22,822 ; of *Calippus* 22,209 ; of *Tycho* 20,181 feet.* The height above the sur-

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* We have stated that Galileo (note to page 336) made the altitude of the higher of the moon's mountains 8800 metres. Hevelius reduced their height to 5200 metres. Riccioli, as M. Arago states, increased Galileo's estimate, and his observations, as calculated by M. Keill, gave for the mountain St. Catherine more than 14,000 metres. Herschel in 1780, (Phil. Trans. for 1780, p. 507 ; also for 1794, p. 40,) reduced again the heights, concluding from his observations that the loftiest did not exceed *a mile and a half*. The latest investigations have restored them nearly to Galileo's first estimate.

We state, for the information of some who have not paid attention to the subject, that these heights are determined, either from the shadows of the peaks on the central plain of a crater or the exterior surface, or by noting the position of a summit when it first becomes illuminated, and calculating therefrom ; the higher the peak, the longer will be the shadow, and also, the sooner its top will be tipped with light. Should it hereafter be established that the moon has an atmosphere, it must be too slight to affect appreciably the altitudes determined : with regard to the breadth of the craters, there can be no more doubt, than with respect to the diameter of the moon itself.

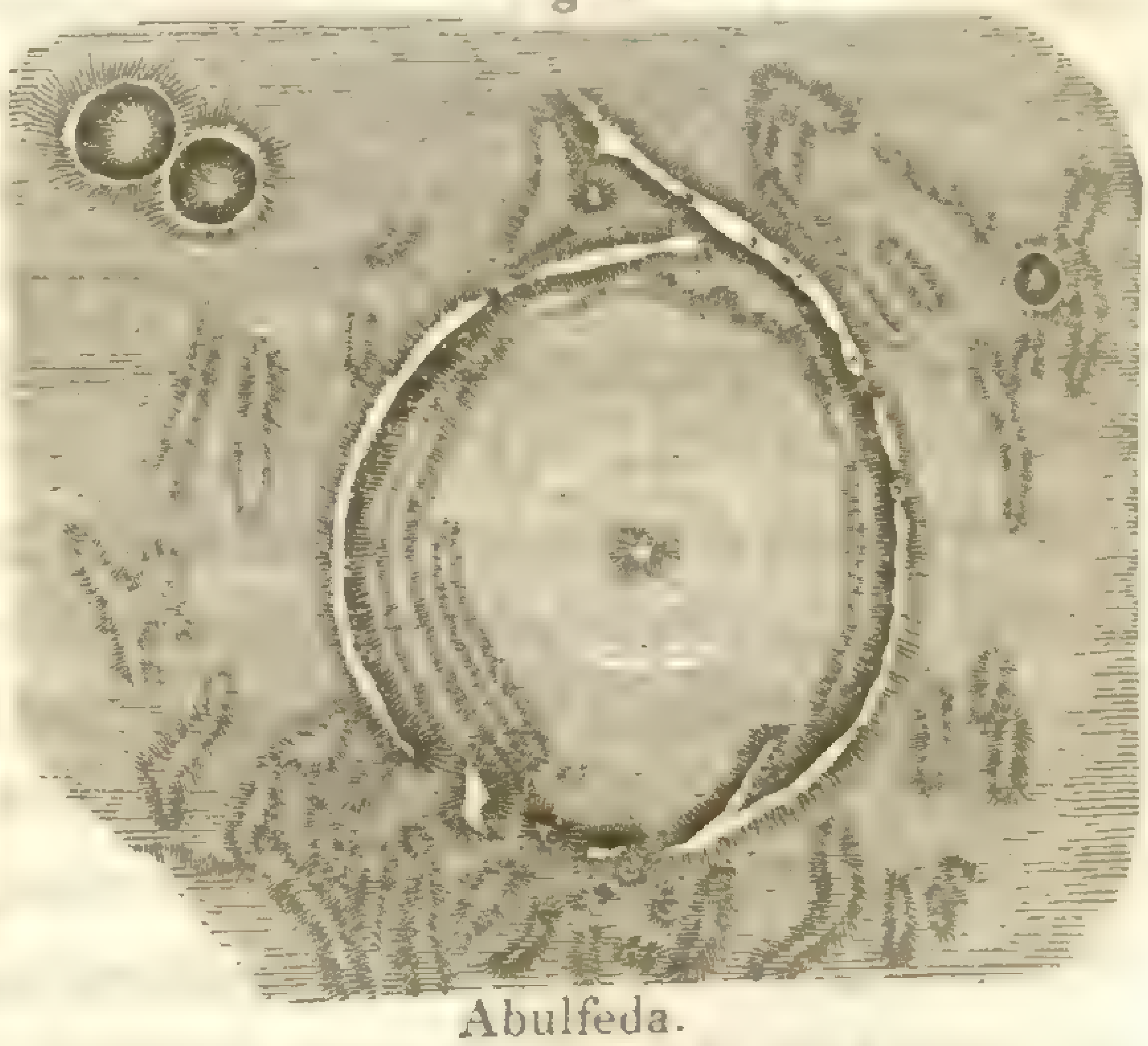
There are many who receive with scepticism the facts we have stated, or even deny where they know nothing. It is taking a high ground, to dispute with all face exterior to the cone, is said by Beer and Mädler to be often but one half or one third the height above the bottom of the crater; the outer slopes are generally steep, so that the margin appears like a raised rim around the pit.

Mr. Nasmyth figures one which is filled to its summit, and is tipped with a plain 40 miles in diameter;* looking, he says, as if "brim full of molten lava," having cooled, probably, when thus filled.

Fig. 1.

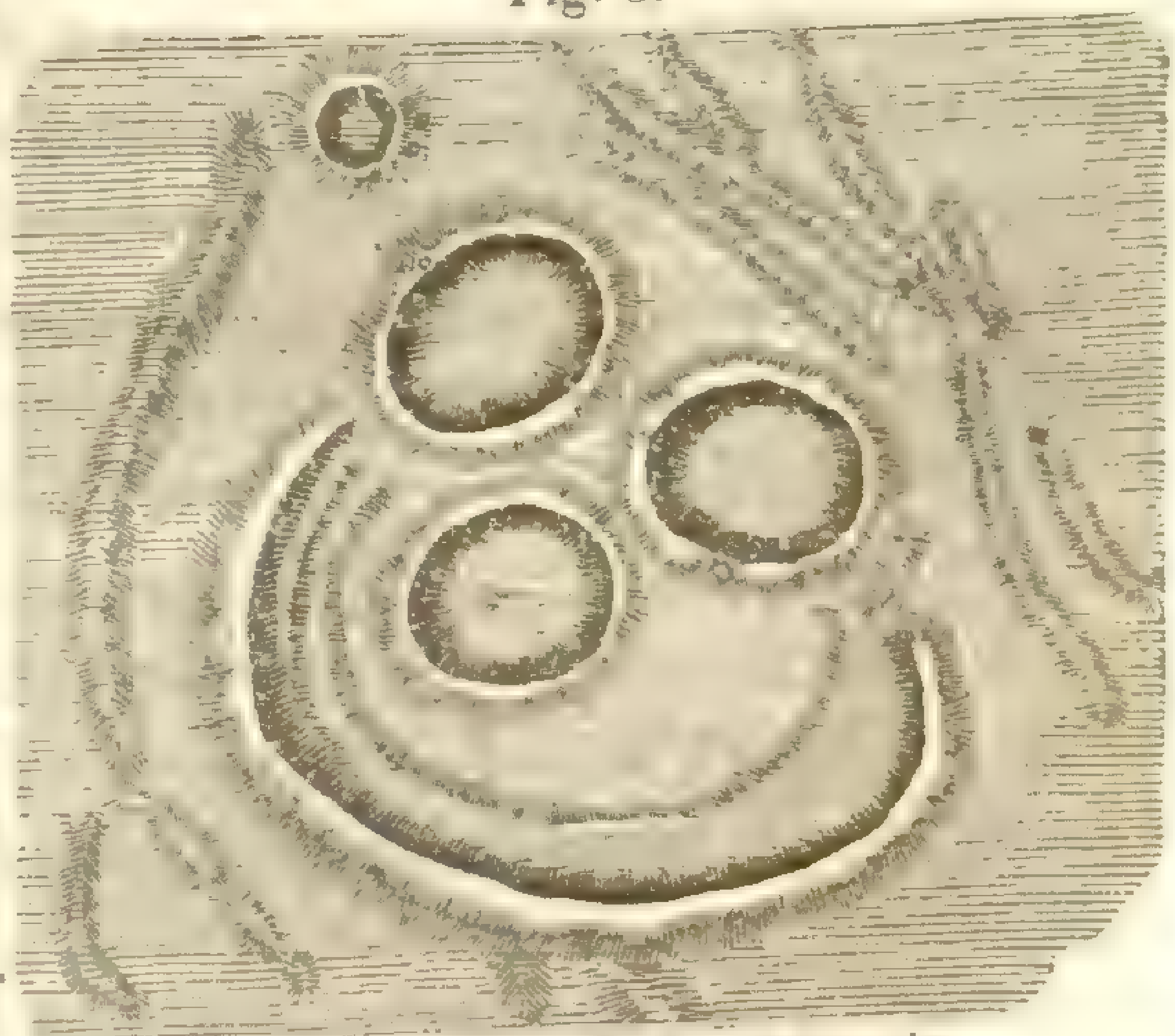
Timocharis.

Fig. 2.



Abulfeda.

Fig. 3.



Heinsius, seen a little obliquely.

The largest craters are not contained in the highest mountains: on the contrary, they are of less altitude than those of medium size, and to a certain extent the height varies inversely with the diameter.

The pits are generally circular, and sometimes almost artificially regular. There are others which consist of two or more coalesced cir-

the astronomers since Galileo, and one to which ignorance alone would presume. The best antidote we can propose to such presumption, is to take the first opportunity which offers, to look through a good telescope at the moon's surface, and examine its features for themselves. We predict that they will soon become conscious of a growing willingness to be humble learners of such men as Herschel and others who have made the moon their study.

* Mem. of the Roy. Astronom. Soc., xv, 152.

cular pits. In still others, especially the largest, the enclosing walls are broken into a series of ridges, sometimes with large openings like the break of an eruption: yet even then the irregular forms may generally be referred either to a single circle, to a combination of circles, or to the formation of successive ridges one within another. The bottom of the pits though generally flat or nearly so, not unfrequently contains small cones, or ridge-like elevations; we call them small, though some are 5000 feet in height, for they are mere dots in the immense basin. Over the exterior slopes there are many lateral cones of the same *small* dimensions, and occasionally one as large as Etna may be distinguished, besides others of different sizes to a few hundred feet in breadth. There are also circular craters within the larger pits, which are of various dimensions.

The pointed cones or peaks, excepting those immediately connected with the pit-craters, are few in number. According to Beer and Mädler, *Dörfel*, the most elevated lunar peak measured, is 24,945 feet in height; it is situated in the lunar Appenines: *Huygens*, another peak, is 18,209 feet in altitude.

The mountain ridges are peculiar in being generally elongated elevations, or clusters of such elevations, without valleys intersecting their declivities, and thus very unlike the chains of our globe. As M. Rozet and others have remarked, there is no water on the moon to wear out valleys.

Many of the depressions called seas, of which the *Mare Serenitatis*, and *Mare Crisium*, are examples, vary in breadth to five or six hundred miles, and notwithstanding their size, they are identical in character with the great pit-craters, their extent and less depth being their only characteristics. This view is suggested by M. Rozet, and their features clearly sustain it. They contain cones and circular areas like the better defined pits.*

The light streaks alluded to form radiating lines around large cones, and especially about *Euler*, *Kepler*, *Copernicus, and Aristarchus*. They are from one to five hundred miles in length, and cross ridges and depressions, without interruption. They coalesce about the summit of *Kepler*, so that the whole surface appears nebulous.

* The "seas," according to M. Rozet, have escarpments of 45 degrees, some of which are 400 metres in height. In the interior there are annular cavities, perfect rings in shape, the diameter of which attains sometimes to 100,000 metres.

The various pit craters differ in shade of color, or rather in the degree of light they reflect; and ten different degrees are distinguished in the work of Beer and Mädler. 1 to 3, he says, may be described as gray, 4 to 5 light gray, 6 to 7 white, 8 to 10 shining white. The so-called seas, though but slightly depressed, are sometimes very much lighter than the surrounding surface. In some instances, as these authors state, two pits, side by side, alike in size and features, so differ in brilliancy that one is wholly obscured in the full moon, while the other still shines: the two are seen together again as soon as their shadows reappear. The brightest craters are *Aristarchus*, *Werner* and *Proclus*. *Aristarchus* is 7629 feet in depth. It has a point of greatest brilliancy, besides two or three separate circular spots remarkably light. *Werner* has a single brilliant point. *Proclus* has brilliant walls, yet is dark at bottom.

Sir Wm. Herschel published the first account of existing volcanic action in the moon. In a notice of three lunar volcanoes,* he says that two of them, on April 19, 1787, were either nearly extinct or about to break out, while the third was in actual eruption. April 20, he observed that the active one burned with greater violence; and he estimated that the fiery area was above three miles in diameter. All the adjacent parts of the crater seemed to be illuminated by the eruption.† The other two volcanoes, he says, resembled large pretty faint nebulæ, that are gradually much brighter at the middle, but no well defined luminous spot could be distinguished. Herschel alludes also to an eruption seen by him previously, in 1783.

Such are the general facts, which call for explanation, to wit: the existence of circular pit craters, 5 to 150 miles in diameter, and five to twenty-four thousand feet in depth;—the great number of these pit craters, and their peculiar features;—the depressions of a similar character of still larger area;—and the various degrees of il-

* Phil. Trans. for 1787, p. 229.

† It is supposed that this crater was that called *Aristarchus*, or the *Mons Porphyrites* of Hevelius. *Aristarchus* is described as apparently in action in 1821, by H. Kater, in the Philosophical Transactions for 1821, p. 130; also by Rev. M. Ward, at nearly the same time, in the Memoirs of the Royal Astronomical Society, i, 157; also the following year by Rev. Fearon Fallows, in the Philosophical Transactions for 1822, p. 237. Dr. Olbers observed *Aristarchus* at the same time with Kater in 1821, and attributed the light to the reflection of the earth's light by its smooth rocks.

lumination of the craters. Well may the Vesuvian vulcanist look with doubt upon such vast gulfs; for he finds in his well known volcano, nothing parallel in kind or degree. The little dark hole at the top of his mountain, has scarcely a single point of resemblance to the open walled areas of the moon.

But the case is different with Kilauea, to which we now direct our attention. We observe that the facts this crater presents are precisely the same in kind as those of the moon.

1. The crater is a large open pit, exceeding three miles in its longer diameter, and nearly a thousand feet deep.

2. It has clear bluff walls through a greater part of its circuit, with an inner ledge or plain at their base, raised 340 feet above the bottom.

3. The bottom is a plain of solid lavas, entirely open to day, which may be traversed with safety; over it there are pools of boiling lava in active ebullition, and one is more than a thousand feet in diameter. There are also cones at times from a few yards to two or three thousand feet in diameter, and varying greatly in angle of inclination. The largest of these cones have a circular pit or crater at summit.

Compare these characters severally with the lunar craters, and an identity will be perceived even to the ledge that surrounds the lower pit, and the various forms of the cones. A large number of the lunar craters have an inner circle either as a terrace or ridge. The ledge within *Timocharis* (figure 1) is very similar to that of Kilauea, and is continued around the whole pit unbroken as in the Hawaiian crater. The other figures illustrate the same feature in different conditions. Some of them too contain circular areas with the rim scarcely elevated, (figure 2,) and others raised into cones, (figure 3): and so, in Kilauea, there are at times boiling lakes in the bottom plain, and other pools constitute the summits of cones which they themselves have formed. To appreciate the comparison, it must be remembered that the Hawaiian pit-crater is upwards of three miles in length, and averages nearly half this in breadth; and that the largest boiling pool, though more than a thousand feet in diameter, is still a small spot in the extensive area. During times of greater activity, the whole pit is in every part lighted with the fiery lavas, overflowing at times from the numerous lakes, and jetted from the many cones.

The *circular* or slightly elliptical form of the moon's craters is also exemplified to perfection. For the lakes of Kilauea have this shape; and although the pit itself is oblong, owing to its situation on a fissure, other large though extinct pit craters of Mount Loa are quite as regularly circular in form. Some are twins; that is, are made up of two or three coalescing circles.

We have chosen Kilauea for these illustrations because it is now in action, and the features appealed to have been familiar to us, since the first publications of Admiral Byron, and Rev. Charles S. Stewart. I may add that the facts are finely illustrated in the Narrative of the Exploring Expedition by Capt. Wilkes,* and they will be farther detailed in the Expedition Geological Report on the Hawaiian Islands, now in course of preparation. The exact application of these facts, as far as regards general features, to the *summit* crater of Mt. Loa, will be found fully sustained by the plans and views accompanying the Narrative.

Whence all this close resemblance to the lunar craters, while other volcanoes are so different? It arises from the fact that the action at Kilauea is simply *boiling*, owing to the extreme fluidity of the lavas. The gases or vapors which produce this appearance of active ebullition, escape freely in small bubbles with little commotion, like the jets over boiling water; while at Vesuvius and other like cones they collect in immense bubbles before they accumulate force enough to make their way through; and consequently the lavas in the latter case are ejected with so much violence, that they rise to a height often of many thousand feet and fall around in cinders. This action builds up the pointed mountain, while the simple boiling of Kilauea makes no cinders and no cinder cones. Still, although the lavas of this crater are not thrown to a great height, they may make cones of any angle, even by overflowing alone; especially by small or partial overflowings, which melt together, cooling at the same time rapidly. They thus sometimes raise a steep rim around a pool. This point has been well presented by M. C. Prevost,† and in another place we shall mention many facts in illustration of it.

If the fluidity of lavas, then, is sufficient for this active ebullition, we may have boiling going on over an area of an indefi-

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* See Narrative, Vol. iv, p. 125, and the map of part of Hawaii in Vol. vi.

† Bulletin de la Soc. Geol. de France, xi, 1839 à 1840, p. 183.

nite extent; for the size of a boiling lake can have no limits except such as may arise from a deficiency of heat. The size of the lunar craters is therefore no mystery. Neither is their circular form of difficult explanation; for a boiling pool necessarily, by its own action, extends itself circularly around its centre.* The combination of many circles, and the large sea-like areas are as readily understood.†

With so perfect a correspondence, and so satisfactory explanations by means of an appeal to facts, it is hardly necessary to enter a protest against the ordinary view that these craters are the result of cinder eruptions.‡ We remark only that such eruptions will never take place except from small vents, for the cold which gives the viscidity on which they depend, necessarily contracts the area. In a large pool the fluidity is such that the rising vapors pass off freely: the ejections over its surface, excepting those at the margin, will fall back again into the pool, as in boiling water and Kilauea, and could neither rise to the height nor make such curves as are represented by Mr. Nasmyth. Instead of a large open crater having greater projectile force in proportion to its size, it will actually have far less; and within certain limits the force may be inversely as the diameter, though dependent also on the size of the chimney above.

Any vents in the moon in which the fires had partially subsided, would have densely viscid lavas from partial cooling; and in these there would be loftier ejections like those of ordinary volcanoes, forming high conical peaks with narrow openings, if any, at summit.

The great depth of the lunar pits seems to require another element for its explanation, in addition to what has been presented. This is supplied by the fact of the less specific gravity of substances on the moon; for objects on its surface have but one-sixth the specific gravity they have on the earth: that is, iron would

* Mr. Nasmyth suggests that the quietness of the lunar atmosphere may account for the regularity of the circles.

† M. Rozet observes, in his article referred to, that the moon's craters do not resemble those of our volcanoes: and he explains them by supposing that during the cooling of the moon's surface there were *whirlpools* or circular flowings, which carried the scoria from the centre to the circumference, and thus accumulated the enclosing ridges. We see no cause for the existence of whirlpools; nor for such a result from vortical movements.

‡ See the views and remarks of Mr. J. Nasmyth, *loc. cit.*

weigh but one-sixth what it does here. The lavas would therefore not only be specifically lighter, but would become more blown up with the vapors, or more spongy. On the same ground too, we understand why the moon's great craters should so generally terminate in a raised rim, while those of the earth, like Mount Loa, have very gently sloping sides and summit. This raised rim is fully illustrated about the Kilauea pools, as we have already stated: but in large overflowings, the earth's lavas, owing to their weight, flow far away by gravity, and this feature is therefore never exemplified on the earth on the same grand scale as in the moon.*

We may therefore say unhesitatingly, without fearing an impeachment of our sobriety, that the moon's volcanoes are in fact volcanoes, either extinct or active, although the craters would receive comfortably more than a score of Etnas. We also comprehend the important fact, that a cooling globe would become at first a scene of great boiling lakes from the hardening of some portions;—that on a farther diminution of heat, these lakes would partially cool, excepting points or areas of greatest heat, and thus a subdivision of them would result: or else, they would *gradually* contract their overflowings, and so, as gradually, contract the size of the vent, obliterating all evidence of the former size: or again, they would more *abruptly contract*, and consequently form an inner ledge concentric with the outer walls, and perhaps also other concentric ledges still smaller.

This is well illustrated in the figures, and nothing could better indicate the mode of action which characterizes the moon's craters, for we may trace out the successive diminutions. In *Heinsius*, (figure 3,) which is forty-eight miles in its longer diameter, this is beautifully shown; there is one low ledge within another nearly concentric, and finally a smaller circular pit, of twelve miles breadth,—no mean size, though we call it small. An outer concentric ridge is also apparent through part of its circuit, which may have been a still earlier outline; and being lower than the ridge next within, it illustrates the statement, if the hypothesis be true, that the larger craters have lower walls. It is however possible that it may have resulted from a subsi-

* The elevation theory of Von Buch has been supported from facts in the moon. We offer nothing here on that subject.

dence in the area around, as has happened at Kilauea. The same facts are shown by the mountains *Abulfeda* and *Timocharis;* and we have already remarked that the crater of the last mentioned has very nearly the features of the Kilauea pit. Again they might finally so far diminish their size by the cooling in progress, that there would no longer be free ebullition, and the vapors having to force their way up, would break through with explosive violence, producing an alternation it may be of cinder and lava eruptions, or cinder eruptions alone at summit, and raising up conical pointed peaks. These different phases, in connection with fissure eruptions and upliftings from contraction, from both which causes ridges might result, give us a complete and comprehensive view of the origin of the moon's features.

Are the lunar craters still active? To a very great extent the surface has evidently cooled, and whether there are any active points is a matter of doubt. But without admitting igneous action at the present time in some parts, how can the facts mentioned with regard to the difference in the light of different portions of the moon's surface (p. 341) be satisfactorily explained? This difference may possibly be partly accounted for on the ground, (borne out by Kilauea,) that the bottom of a crater may have a smoother surface than the declivities or plains exterior. Perhaps also there is something attributable to a difference of material, though this is not probable. If these explanations are received as sufficient for the craters, they fail of satisfying us with regard to the light streaks which are so remarkable about some cones—coursing over ridges and depressions without interruption. The fact of illuminated walls to a crater when the bottom is not illuminated, and the general diffusion of light when one or more bright areas of small extent may be distinguished, are also points not easily understood on the above suppositions. May it not be, that we should attribute some of the instances of lighted areas to a covering of vapors from the igneous action beneath? The light streaks are not depressions, and therefore not broad fissures having the great width they exhibit; but they may be *regions* containing many fissures from which vapors are escaping, and by the coalescence of such areas, the summit of a crater like *Euler* might appear illuminated. Such vapors might so cover the bottom of a crater that the walls would appear brightest. Moreover they might leave the cones within a crater still distinct; for if spread out at a height of five hundred feet above the bottom, they would still in many instances be more than ten thousand feet below the summit, and far below too the tops of interior peaks.

As there is little or no water in the moon to aid volcanic action, sulphur has probably played an important part in its igneous changes; for this is not only a prevalent means of igneous operations on our globe, but occurs in meteoric stones, pyrites being one of their common constituents. We may therefore believe that, wherever there is action in the moon, sulphur and any other vaporizable material present, are constantly escaping either as simple vapor or in some gaseous combination, and forming a very low covering over certain portions.

As we have observed, the existence of actual volcanic eruption in the moon is still doubtful, and we must look to new facts to settle the point. But we cannot doubt that the surface in *former* periods has been everywhere in violent action, and that its pools of fire were once measured by scores of miles instead of by hundreds of yards, as with our existing volcanoes. And many of these immense basins remain still open for examination, presenting indications of the various changes which accompanied the gradual decrease of igneous action during the cooling in progress. A map of the moon, if there is any truth in these views, should be in every geological lecture room; for no where can we have a more complete or more magnificent illustration of volcanic operations. Our own sublimest volcanoes would rank among the smaller lunar eminences; and our Etnas are but spitting furnaces.

In continuation, I would ask attention to some thoughts bearing on our own planet, which are suggested by this study of the moon's surface.

I. If the earth was once a melted globe, it must have passed through the same phases as the moon, with this *very important difference*, that the whole surface during its progress was subject to the denuding action of waters, and from the first had valleys and sedimentary rocks in progress. It must have had originally its boiling pools of vast extent; which as the action decreased in violence would more or less gradually contract. Are there any remains of these great craters? Or have they disappeared by a decrease in the volcanic action and thus graduated into existing mountains, or have they been swept away by the changes of time? M. von Buch has described a circular area on the island of Palma, one of the Canaries,* six miles in diameter, which has been compared to a lunar crater, with some appearance of reason. It is in fact hardly twice the diameter of Kilauea, which it otherwise resembles. On Mauritius there is a similar area fifteen miles in diameter, surrounded by precipitous walls composed of the edges of strata dipping outward.† Either it is a volcanic mountain whose centre has fallen in, as suggested by M. Bailly, or it is the remains of a great pit-crater. I merely state the fact without expressing an opinion. Other instances might be mentioned, but this will suffice. At the present period, few active boiling pits remain, and Kilauea is the only one whose characters have been well determined. The surface fires of the globe have so far subsided in action, that in nearly every existing volcano, cinder-ejections characterize the action at summit, and eruptions of lavas in streams are confined to fissures through the sides and flanks of the mountain.

II. We are led by the facts displayed, to remark also on the *origin of the mineral constitution of igneous rocks.*

It has been a difficult problem for solution, why volcanic regions should have a centre of solid feldspathic rocks, unstratified and compact, while the exterior consisted mainly of basaltic lavas. Scrope, Von Buch, and other writers on volcanoes, have mentioned instances of this structure; and it seems to characterize generally the large volcanic mountains. It is well exhibited when the elevations are cut through by gorges; and when not, the clinkstone appears often at the summit of the cone or dome. The explanations we here venture, proceed on two principles:

1. *The motion which belongs to a boiling fluid.*
2. *The less fusibility of feldspar than the other ingredients.*

In the great boiling pools, there will necessarily be a rising of the fluid, in the hotter part, and a flow away towards either side, producing a kind of circulation. This is no hypothesis, as the fact may be witnessed in any boiling cauldron; and the lavas of Kilauea are a visible example of it. The ebullition in lavas

* Desc. Phys. des Iles Canaries. Paris, 1836, p. 281.
† Darwin's Volcanic Islands. London, 1844, p. 30.

on the earth, proceeds principally from the vapors of water and sulphur, which are constantly rising through them, inflating them more and more as they ascend, and finally escaping in bubbles at the surface. Now the feldspar being the less fusible part of the lavas, would thicken somewhat, wherever the temperature became too low for complete fusion; the more liquid portion would then ascend most easily, being carried along by the inflating vapors, and much of the feldspar would thus be left behind, and it might be in a nearly pure state. The centre of the volcano under this action, becomes necessarily feldspathic. The summit might therefore eject either basaltic or feldspathic rocks from the material of the vent; though when the action was violent and deep, it would eject feldspathic rocks alone.

At the same time the *basaltic* lavas, descending laterally in this system of circulation along the sides of the great central conduit, may pass out as flank eruptions through fissures. Besides, there will also be basaltic ejections from sources of lavas at a distance from the central conduit, where they have not been subjected to the separating process described; and this may be the more common source.

Mountains with a feldspathic centre, and basaltic layers forming the circumference, are therefore quite intelligible without supposing the feldspar to have been first thrown up, or appealing to a different system of fissures for their origin, and the examples which the moon presents, are more extensive than is necessary to explain the widest facts on the earth.*

In these remarks we have spoken of the lavas as consisting mainly of feldspar and augite, their more common constitution; but we use the terms in a general sense, understanding by feldspar one or another of the feldspar family of minerals, and by

* It is common to say that certain domes of trachyte were thrown up in a *pasty* or imperfectly fluid state,—in order to account for the fact that there is no appearance of the rock's having flowed in streams. Without intending to refer the origin of these domes to any particular cause, I would suggest the query, whether, if their formation was subaërial, this *pasty* state does not necessarily imply that the ascending vapors would have found some difficulty in escaping, and would have broken through with explosions, as explained in the foregoing pages; and consequently that there would have been scoria and cinders accompanying the ejections? or may we believe it probable, that the paste was so dense that water would not make its way up and escape as vapor? Is this last supposition borne out by any existing example of subaërial volcanic action?

augite the remaining fusible material, whether ordinary augite (silicate of lime, magnesia and iron) or silicates of one or more of these bases or alumina in other combinations.

There is some difficulty in applying this hypothesis to particular cases, on account of our ignorance of the actual fusibilities of the materials of the lava, in the condition in which they are placed; for we know that an infusible mineral may be held in fusion under certain circumstances, or with certain mineral associations, far below the temperature at which it fuses: or, previous to the commencement of cooling it may be in some other combination.

We should infer that the process which separates the feldspar, would also separate any excess of the more infusible mineral quartz. This may not follow: still it is a remarkable fact that the quantity of quartz contained in trachyte is often in great excess, as analyses have shown. But why is not the infusible mineral chrysolite also detained? The fact appears to be, that it is of subsequent formation. The small proportion of silica it contains implies a deficiency of this substance, while, as we have stated, in the feldspathic rocks there is often an excess. It may, therefore, under certain circumstances proceed from the basaltic material, for its elements are the same in different proportions. Subsequent investigations may give us more light on this point.

The general principle which we have above brought forward, is well illustrated in the fact that the scoria or surface glass of any vent, where it occurs, is the most fusible part of the lava, consisting in general of ferruginous or alkaline silicates, and containing no magnesia. On account of the diminished heat, this material alone remains sufficiently fluid to be inflated and borne up to the surface by the rising vapors: and this takes place in spite of superior gravity.

We hence comprehend the *rapid cooling* which characterizes ejected lavas, *for only a part of the material is in complete fusion.*

The actual nature of the *cooled igneous rock* may be more correctly understood, if we consider that the minerals present will depend, not only on heat and pressure and the causes above alluded to, but also on rate of cooling. The effect of slow cooling is exemplified in the feldspathic centre of a volcanic mountain. Being wholly enclosed by rocks, the heat of fusion passes off slowly, and owing to the pressure of its own superincumbent portions, the rock is compact. Whatever augite may be present, instead of appearing as augite, will take the form of hornblende, a mineral which requires slow cooling, and differs from augite in the crystalline form which it thus receives. In corroboration of this statement, hornblende is common in trachytes and such feldspathic rocks. The same remarks apply to mica: and other minerals also may form according to the elements present. Chrysolite is not met with: it occurs only where there is a more rapid rate of cooling, as in the formation of ordinary basaltic rocks or lavas.

Farther we observe that with a still more gradual rate of cooling, the whole feldspathic rock becomes crystalline in texture like a granite or syenite, and it is well known that granite-like or syenitic rocks or peaks occur in some volcanic regions, whose interior has been laid open by denudation. Many minerals too might crystallize under these circumstances, which with more rapid cooling would not be distinguishable.

The boiling process in a large volcano, therefore, in connection with the circumstances of temperature, rate of cooling, the fusibilities of different minerals, and the other causes alluded to, will account for the various features, positions and relations of igneous rocks, and for many facts relating to the distribution of igneous minerals.* We may hence reasonably infer that granite and granite minerals may form under the same circumstances, if the elements are present in the material in fusion; for the syenites alluded to are closely allied rocks in texture and character. At a former meeting of this Association, it was suggested by me that *some* regions of granite peaks may have been centres of ancient igneous action; and their being surrounded or bordered by hornblendic rocks, seems to point to some actual analogy with the trachytic centres and basaltic circumference of mountains admitted to have been volcanic.

The opinion that the nature of the resulting rock is directly connected with the nature of the rock which had entered into fusion, cannot be maintained if the above views be true. On the contrary, it appears that while the result may thus be varied, the

* The general causes referred to, act under the guiding laws of crystallogeny, which laws regulate the particular positions of minerals according to the principles exemplified in segregations or radiated crystallizations, and the laminated or cleavable structure of igneous rocks.

mode of distributing minerals in a volcanic focus by the boiling process, may produce from the same material, rocks of a predominant feldspathic character in one place, and rocks of a hornblendic or augitic character in other places. Simple feldspathic granites may be fused and ejected as feldspathic rocks, like those of porphyry dikes. But it is an interesting fact, that the rock of most dikes is of the augitic (or hornblendic) kind, like the dikes of volcanoes that rise from sources in which the *separating* process could not have been operating.*

We also arrive at the important conclusion, that rocks perfectly compact in texture may be of subaërial origin, as we have pressure from the fluid lavas themselves in the volcanic focus.

Another deduction proceeds from the facts stated ;—that the same igneous rocks may occur of all ages, provided the atmosphere or waters of the earth were not too warm for the more rapid rate of cooling required for uncrystalline rocks. Scorias, basalt, trap, porphyry, syenite, granite, have no relations to one epoch rather than another, beyond what may depend on the circumstance just mentioned. Whenever therefore in the history of the world, the variations in heat, pressure, and rate of cooling, now possible, may have taken place, similar rocks to those of the present day may have been in progress :—and as far as the variations of former times, in these respects, may now take place, former rocks and minerals may still be in progress. In this statement it is implied that the necessary elements are present in the fused material.

III. *Origin of Continents.*—The moon gives us hints on another topic of great interest, relating to the distribution of land and water on our globe. We have mentioned that there is a large area covering nearly one third of the hemisphere facing the earth, which is mostly free from volcanoes, while on other parts the craters are closely crowded together. We may therefore reason-

* Mr. Darwin has accounted for the distribution of feldspathic and augitic rocks in volcanoes, on the ground of their different specific gravity. But with this cause alone, the lower parts of the feldspathic peaks should be expected to contain the heavier augitic material, which is not the case. He also argues that the feldspar would rise in the fluid as crystals, and so the augite sink. But we know in the first place, that crystals do not appear till incipient solidification, and if the augite and feldspar were both in distinct crystals, where would be the fusion? Again, the feldspar rocks are *amorphous*, except with a very slow rate of cooling; and how then can the existence of appreciable crystals be assumed?

ably infer, that over this naked portion, the surface first became solid, and has therefore cooled the longest and to the greatest depth. Consequently, the contraction from cooling, which was going on, would take place most rapidly over the thinner and more yielding volcanic portion; and unless the ejections made up the difference, this part would become somewhat depressed. A melted globe of lead or iron in the same manner, when cooling unequally, becomes depressed by contraction on the side which cools last. Now on our own globe, the continents have to a very great extent been long free from volcanic action. A glance at a map of Asia and America will make this apparent. It is usual to attribute this almost total absence of volcanoes from the interior of the continents to the absence of the sea; but it is fatal to this popular hypothesis, that the same freedom from volcanoes existed in the Silurian period, when these very continents were mostly under salt water, a fact to which the wide spread Silurian rocks of America and Russia testify. Over the *oceans*, on the contrary, all the islands excepting the coral, are igneous—and the coral may rest as we have reason to believe on an igneous base.

It is therefore a just conclusion that the areas of the surface constituting the continents were first free from eruptive fires. These portions cooled first, and consequently the contraction in progress affected most the other parts. The great depressions occupied by the oceans thus began; and for a long period afterward, continued deepening by slow, though it may have been unequal, progress. This may be deemed a mere hypothesis; if so, it is not as groundless as the common assumption that the oceans may have once been dry land, a view often the basis of geological reasoning.

Let us look farther at the facts. Before the depression of the oceanic part of our globe had made much progress, the depth would be too shallow to contain the seas, and consequently the whole land would be under water. Is it not a fact that in the early Silurian epoch nearly every part of the globe was beneath the ocean? So we are taught by the extent of the formations. The depth of water over the continental portions would be very various; but those parts which now abound in the relics of marine life, were probably comparatively shallow, as amount of pressure, light, and dissolved air, are the principal circumstances influencing the distribution of animals in depth, and acted formerly, we may believe, as at the present period. Here then we see reason for what has been considered a most improbable supposition, the existence of an immense area covered in most parts by shallow seas and so fitted for marine life.

If we follow the progress of the land, we find that with each great epoch there has been a retiring of the sea. In the coal deposits we have an abundant land vegetation. Subsequently, the progress on the whole was giving increased extent and height to the land and diminishing the area of the waters. Instead therefore of a bodily lifting of the continents to produce the apparent elevation, it may actually have been a retreating of the waters through the sinking of the ocean's bottom. The process however has not been a continuous one: for during each epoch,—the Silurian and the more recent,—there have been subsidences as well as seeming and actual elevations, and various oscillations of the continental surface, from subaërial to submarine and the reverse. When contraction had once taken place over the continents as well as under the ocean, there may have afterwards been expansions again through the return of heat from some cause. And thus various irregularities have taken place, such as the rocks indicate. In the tertiary period and since, the apparent rise of the land has been still to some extent in progress. And is there any evidence that this could have arisen from a sinking of the ocean's bed? The evidence is undoubted. For Mr. Darwin has shown satisfactorily, (and farther observations to the same end, and to many interesting conclusions, will be presented in the writer's geological report on the Pacific), that a subsidence of some thousands of feet has taken place since the corals commenced their growth. Every coral island is a register of this subsidence.*

And why should not the ocean's bottom subside, as well as the land? What has given the continental portions of our globe their elevation, as compared with other parts, if not the unequal contraction of the whole? Can we safely affirm—in words of high authority—"that the stability of the sea and the mobility of the land are demonstrated truths in geology,"† when mobile land forms also the bed of the ocean, and its changes must affect the

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* See Silliman's Journal, xlv, 131, 1843.

† Leonard Horner, Esq., Anniversary Address before the Geological Society of London, January, 1846; Quarterly Jour. of the Geol. Soc., No. 6, p. 199.

stability of the superincumbent waters; I ask, can we safely make this affirmation, until we know something more certain than past investigations have revealed, about the geological history of the two-thirds of the surface of our planet that are concealed beneath its oceans?

In our conclusion from the above reasoning, we fall in nearly with the views presented by a distinguished French geologist, M. C. Prevost, who has argued with much force in favor of subsidence as a cause of the apparent elevation of the land: though it may be right to state that these conclusions were arrived at previously to seeing his memoir.* There appear to be many objections to the opinions of M. Prevost, as they are expressed by him, inasmuch as no allowance is made or admitted for minor disturbances and actual elevations by subterranean forces. His views however are well worthy the attention of the geological enquirer.

The principles explained place the general theory of change of level by contraction upon something better than a hypothetical basis, and are believed to explain the actual causes by which the changes have been produced. They correspond moreover with the view that ruptures, elevations, foldings and contortions of strata have been produced in the course of contraction. 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.

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* The general theory of changes of level by contraction and expansion, and the rise thus of continents, was first presented by Mr. Babbage and De la Beche. M. C. Prevost takes the different ground that all seeming elevations are the result of subsidence. His propositions are as follows, (Bulletin de la Soc. Geol. de France, xi, 1839 à 1840, p. 186):—

"1. Que le relief de la surface du sol est le resultat de grands affaissements successifs, qui, par contre-coup, et d'une manière secondaire, ont pu occasionner accidentellement des élévations absolues, des pressions latérales, des ploiements, des plissements, des ruptures, des tassements, des failles, etc.; mais que rien n'autorise à croire que ces divers accidents ont eté produits par une cause agissant *sous le sol*, c'est-à-dire par une *force* soulevante;

"2. Que les dislocations du sol sont des effets complexes de retrait, de contraction, de plissement et de chute;"

"3. Que les matières ignées (granites, porphyres, trachytes, basaltes, lavas,) loin d'avoir soulevé et rompu le sol pour s'echapper, ont seulement profité des solutions de continuité qui leur ont été offertes par le retrait et les ruptures, pour sortir, *suinter* et s'épancher au-dehors."