Volcanic Craters and Explosions
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have exhausted him, I hope he will move on to Central Asia; and certainly, having seen some of the deserts there, I can promise him something compared with which his pictures of the outlook from the Desert laboratory which he himself inhabits in Arizona, suggest a perfect garden of Eden. There was one other feature of his lecture which impressed me strongly; it was this. It is one of the privileges of the President of the Society to have placed in his hands a printed copy of the lecture which the hero of the evening is about to deliver. I had my copy of Dr. MacDougal's lecture, and satisfied myself that it would be most striking and erudite. But when I came here, I found that Dr. MacDougal, captivated by his own slides, delivered an entirely different lecture. Therefore I must congratulate the Fellows of the Society, because alone to-night, so far as my own experience extends, we have succeeded in obtaining two lectures from the same man. First, there was the address which Dr. MacDougal delivered to us just now; and later on, when the original essay appears in type, imagine the elation of every one when he finds he has secured a second lecture for the same money.

VOLCANIC CRATERS AND EXPLOSIONS.*

By TEMPEST ANDERSON, D.Sc.

THE subject of Volcanoes naturally divides itself into two branches—the Physiographical, or naked-eye one, and the Petrological, which latter deals with the chemical and microscopical structure of the rocks produced. This branch has by itself provided the subject of life-studies by such men as Sorby, Bonney, Teale, in this country, to say nothing of foreign investigators almost equally distinguished; but it is extremely difficult and complicated, and I do not propose to discuss it to-night.

The other branch deals with the physiographical phenomena of volcanic cones, craters, and lava streams; with deposits of pumice, tuff, ash beds; with dykes, sills and intrusive sheets, their structure and mode of production, and their alteration by weathering and other forms of denudation. It may fairly be included in physical geography, and is, therefore, suitable for consideration by this Society. Even this is far too large a subject to be dealt with in a single lecture, so to-night I shall confine myself chiefly to one division of it, viz. Craters and Explosions, and only mention the other branches incidentally and by way of illustration.

If we watch most volcanic eruptions, small enough to be safely approached, such for instance as that of Vesuvius in September, 1898,† we see a discharge from the crater of vast quantities of dust and ashes suspended in steam and various volcanic gases,† while lower down the cone is a discharge of lava, building up in this case a hill, Colle Umberto primo.

These mark two very distinct factors, and according as one or other predominates, the eruption may be classed as of the explosive or effusive type. Thus the eruption of the Soufrière in St. Vincent in 1902 was wholly explosive, no lava being discharged, while in those of the Hawaiian and

* Royal Geographical Society, November 20, 1911.

† Slide shown.

some of the Icelandic volcanoes enormous volumes of very fluid lava are often discharged with scarcely any explosive action.

The early stages of an eruption are often explosive, and the ejecta fragmentary or vesicular in character (ashes, lapilli, pumice), while later on when most of the gases have simmered off the lava flows steadily and cools into a compact mass. Thus the cone of the Campo Bianco † (white field) in Lipari, from which practically all the pumice stone of commerce is obtained, was evidently formed in the early stages of an eruption, during the later stages of which the obsidian stream of the Roche Rossi (red rocks) were formed. The chemical composition of the two is practically identical, while the diverse mechanical structure makes all the difference between the vesicular pumice and the compact obsidian (volcanic glass).

Among the simplest examples of cones are those formed during a single eruption † ; some of these consist of little more than a hole drilled, or rather punched, through the Earth's crust, while the material thrown out by the escaping gases, and which has fallen down around the vent, may consist chiefly of volcanic ash, perhaps mixed with a varying amount of fragments torn off from the country rock,† though in most cases the former much predominates. Occasionally natural sections, like that made by the waves in a tangential direction on the cone of Vulcanello in the Lipari Islands,† or artificial, as where a cutting for a road has been made in a radial direction into the crater of Astroni,† near Naples, expose the structure and show that the beds of ash, pumice, etc., all dip outwards from the centre of the crater,† while if the sections of the beds can be traced round the inside walls of the crater, they appear horizontal.† The inside of the crater is, however, often much obscured by masses of talus, formed of material which has either fallen short of the crater rim or tumbled afterwards from the cliff, the dip of which is of course towards instead of away from the centre. Few cones are, however, so simple as this, especially if they have been the site of repeated eruptions—parts of the cone have been blown out, and the crater enlarged ; and this again has been filled up, wholly or in part, and then re-excavated, perhaps repeatedly. Vesuvius, with its old crater ring of somma partly surrounding it and its big recently enlarged crater, are familiar examples.†

Volcanic explosions have been divided by Professor Mercalli, of the Vesuvian Observatory, into two types, the Strombolian and Vulcanian, according as the gases escape from among materials, more or less fluid or pasty in the first case, or already solidified in the second.

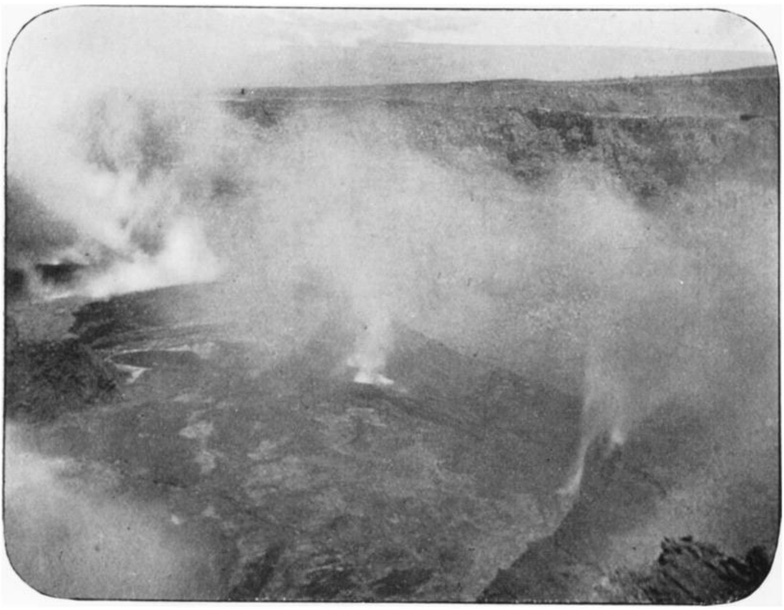
Stromboli † and Vulcano † are both islands in the Lipari Group, north of Sicily, and near enough to be in sight of each other, yet in most respects they present the most diverse characters.

The lava in general consists of silica, which is combined with various bases, of which alumina, iron, and lime are among the most abundant.

† Slide shown.

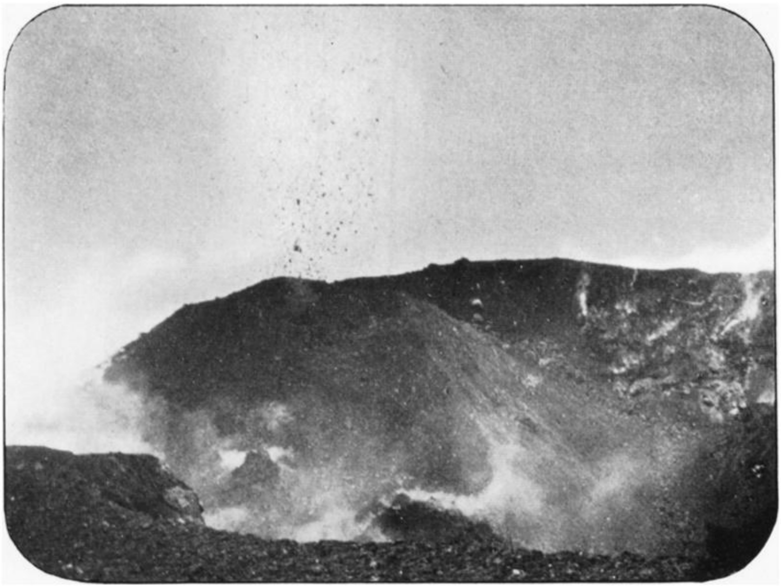
MATAVANU, SAVAII. CORDED LAVA ABOVE HIGH-WATER MARK, PASSING INTO PILLOW-LAVA BELOW.

(*T. Anderson, photo.*)



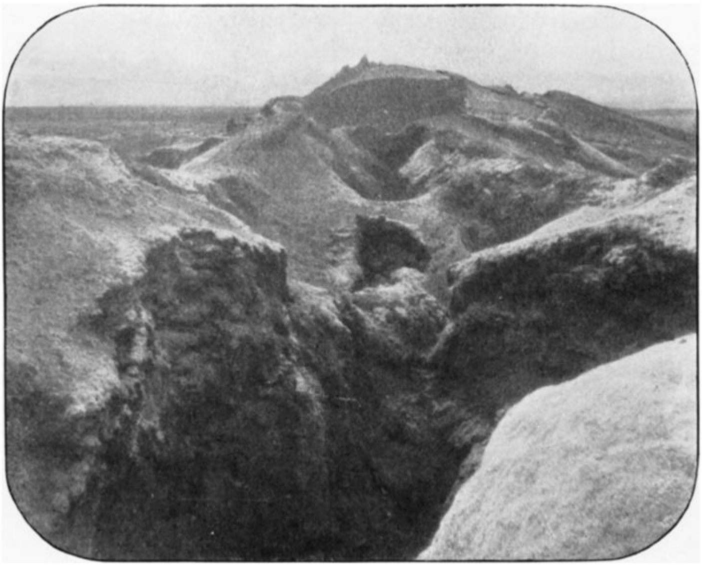
THE CRATER OF KILAUEA, HAWAII. SHOWS REMELTING OF LAVA.

(*T. Anderson, photo.*)



STROMBOLIAN EXPLOSION, STROMBOLI.

(*T. Anderson, photo.*)



LAKIS KRATERE, SKAPTA LAVA, ICELAND. A FISSURE ERUPTION.

(*From Tempest Anderson's 'Volcanic Studies.' Murray.*)

In that of Stromboli, the basic constituents predominate, and the lava is mostly dark coloured, heavy, and readily fusible, while the explosions take place with such frequency and regularity that the mountain is called the lighthouse of the Mediterranean. A typical Strombolian explosion † takes place from a more or less molten mass of this fusible lava, and pasty, red-hot masses are projected high in the air, and often rise so high as to have time to assume ovoid or almost globular forms, and be sufficiently chilled on the surface to retain these forms on falling †; while the escaping gases are often free from dust and chiefly transparent.

On Vulcano, on the other hand, the lava is mostly of a highly acid type, and consequently fusible only with difficulty. The eruptions take place only at intervals of many years, and are then of paroxysmal violence. The explosions † taking place from among the more or less solid materials, carry up entangled in the gases enormous volumes of finely-divided materials (ashes, scoriæ, lapilli, being names applied to different varieties differing mainly in size). The clouds thus produced † often assume forms like cauliflowers † or bunches of grapes, which, though characteristic of this type of eruption, are not confined to volcanic sources. They may be observed when finely-divided particles of soot, suspended in gases at a high temperature, escape from the chimney of a steamer,† as well as from that of a volcano.

The bombs thrown out by this type of eruption are often more or less solid on the surface, at the moment of explosion, while the interior is yet pasty, and still contains imprisoned gas. When in the air the pressure is reduced, and the gases are liberated in vesicles or bubbles, like those in a bread loaf, and the crust gives way owing to their expansion, and produces blocks with an appearance which has procured them the name of bread crust bombs.† I have seen such also among the West Indian volcanoes and also those of Central America.

Though the above types of explosions are named after Stromboli and Vulcano, and are mainly characteristic of them, it does not follow that no explosions of other types are observed on those volcanoes. On the contrary, I have observed and photographed well marked Vulcanian explosions on Stromboli † in 1904. So much for the explosive factor in eruptions.

I must now deal rapidly with the other aspect, the effusive (*fundo*—I pour) or efflusive (*fluo* — I flow). Occasionally the molten magna rises without explosion to the rim of the crater and flows down the side of the cone as a stream of lava: more commonly it insinuates itself as a dyke † or as an intrusive sheet † into cracks or fissures in the substance of the cone, and comes to the surface, somewhere near its foot. If it still contains much steam or other volcanic vapour, this tends to expand and form vesicles and bubbles, in fact, red hot froth, and this solidifies into the well-known cindery or scoriaceous lava.† This often floats on the surface

† Slide shown.

of the still liquid, or, at any rate, pasty lava underneath, and rolls down the ends or sides of the stream with a very characteristic noise. Large fields of lava are thus commonly formed, covered with great rough, sharp-edged blocks, and they present an almost impassable barrier to locomotion. If the lava underneath the layer of scoriæ retains sufficient heat to remain liquid long enough it parts with most of its imprisoned vapour, and may eventually emerge from under the covering and begin to assume the form to be next mentioned. Quite often, however, it originally contained little vapour, or has already lost the greater part when it comes out, and in this case it flows at once with a smooth surface. In either case this molten surface rapidly loses heat, and becomes treacly and viscid. The flow still continuing, this viscid layer is carried forwards and pushed up into a ridge like a cord, and solidifies in that form; while the same happens to the surface of the portion which follows, so that another cord is formed behind the first, and the process is repeated till the stream or sheet of lava is entirely covered with corded structure. I watched this process on the Colle Umberto primo, the new hillock that formed on Vesuvius near the observatory in 1898. The lava streams which were often numerous, were constantly cooling and giving place to new ones. They were not conspicuous by daylight, though they could be readily traced by the pale blueish vapour which they gave off.† At night, however, the red-hot lava became conspicuous in the darkness. A party of us watched the wonderful phenomena on every evening from the top of the observatory, and I was even able to secure photographs † of the streams by the light they themselves furnished. These lava structures must be contrasted with the products of explosive eruptions, such as ashes, scoriæ and pumice.

The great eruption of the Soufrière in St. Vincent was entirely explosive, and the ejecta were in places 200 feet thick. They consisted chiefly of ashes with a certain number of ejected blocks, and the secondary phenomena produced by the contact of rain water with the hot ash were very remarkable.*

The eruption of Santa Maria † in Guatemala, in 1902, was also entirely explosive. The mountain was previous to the eruption a very regular cone, about 12,600 feet high, with only quite a small crater in the summit. By a series of tremendous explosions lasting two nights and a day, an entirely new crater was blown out of one side of the mountain. As nearly as I could measure it, it was seven-eighths of a mile in its longer diameter, and five-eighths of a mile in its shorter, while the precipice exposed in the side of the mountain was at least 5000 feet, say upwards of a mile, high. It is worth remembering that the corresponding precipice left after the eruption of Krakatau in 1883, which has hitherto been considered one of the largest on record, is only about 1200 feet high. In both cases

* T. Anderson and J. S. Flett, *Phil. Trans.*, part i. 1902, parts ii. and iii. 1907; T. Anderson, *Geographical Journal*, 1902.

† Slide shown.

BREAD-CRUST BOMB IN THE CRATER OF CERVO QUEMADO, GUATEMALA.

(*T. Anderson, photo.*)

EXPLOSION CRATER OF SANTA MARIA, GUATEMALA. SHOWS DENUDATION OF ASH DEPOSIT.

(*T. Anderson.*)

also the dust was carried into the higher regions of the atmosphere, and gave rise to remarkable sunset effects.* The surrounding country for many miles was devastated and a large number of lives were lost, but the place is so remote that the eruption did not attract the attention it deserved.‡

The ashes in these two last eruptions, and also in that of Tarawera in New Zealand in 1886, are consolidating by time and pressure into tuff, a soft porous rock, which by the action of rain and streams shows a characteristic feather-like pattern on the surface, and weathers into remarkable ravines.†

The Tarawera eruption was a fissure eruption, a class which has of late attracted much attention. A series of small craters opened along the line of a great fissure several miles long, the chief action, however, being localized in Lake Tarawera, all the water in which was blown out, and the pink and white terraces which formerly existed there were totally destroyed. Percy Smith, formerly Surveyor-General of New Zealand, who was one of the first party to visit the scene of the eruption, told me that he descended 500 feet into the crater which opened in the floor of the lake, and which is now again filled with water.§ Fissure eruptions are also common in Iceland, and are generally accompanied by the discharge of enormous volumes of very liquid basalt lava. The historic eruption of the Skapta Jokul † in the latter half of the eighteenth century was of this class.||

When the early part of an eruption has been explosive, and a cone has been built up in the manner described, the magma which rises in the volcanic chimney (or vent) tends, towards the end of the eruption, to have parted with most of its contained vapour, and the mass often cools and solidifies in the form of a plug, which has been supported by the materials of the cone, acting as a sort of mould or matrix. If now the soft ashes are removed by any of the processes of subaereal denudation, for instance by the action of a river, the plug may remain standing and is called a volcanic neck.† Such are not uncommon, and good instances occur on the Rhine between Bonn and Coblenz, where they consist of columnar basalt, and at Le Puy en Velay in Central France, where the Rocher St. Michel † consists of a mass of agglomerate, *i.e.* angular fragments of volcanic material, which had been churned up and down in the chimney while hot and finally become coherent.

A variation of this process has produced the Domitic Puys in Auvergne, of which the Grand Sarcoui † is one of the best examples. The lava as it issued was so pasty and viscid that it did not run down as a stream, but formed a rounded flattened dome between two cones of fragmentary materials, one of them very perfect, both of which appear to have been formed in the early part of the same eruption.

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* Verbeek, 'Krakatau,' also 'Report of Royal Soc. Com.'
‡ T. Anderson, *Geographical Journal*, 1907.
† Slide shown.
§ See his Official Report.
|| Helland, Lakis Kratere.

A further stage of the same process occurred in Mont Peleé, in Martinique, in the great eruption of 1902, in which the city of St. Pierre was destroyed. A dome was first formed in the bottom of the old crater, but did not nearly fill it. The material of which it was composed contained large volumes of dissolved gases, and broke down as described above in the case of the Soufrière of St. Vincent. The incandescent mixture passed out through a V-shaped notch in the side of the crater, rolled down the mountain-side as an avalanche, and destroyed St. Pierre.

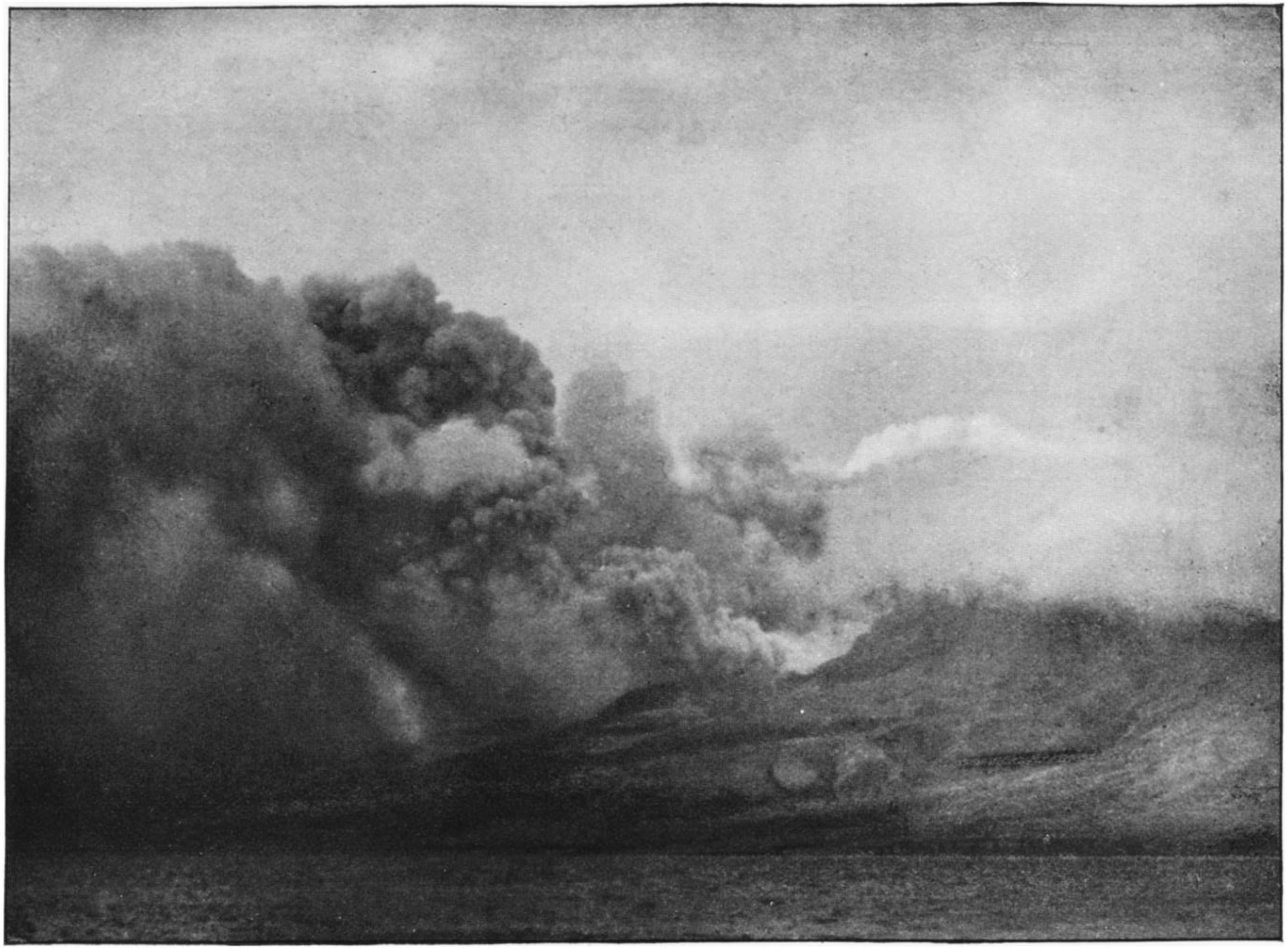
As the eruption became less violent a plug formed in the volcanic chimney as above described, and being pressed forward from below, forced its way through the dome, and formed the famous spine.† It rose to a height of about 800 feet above the top of the mountain, and it is believed that material to the extent of above 1000 feet was actually pushed out; but it was crumbling away all the time, and when I ascended the mountain twice, about five years later, only a rounded stump was visible, with a ring of very active fumaroles marking its junction with the dome, and with the talus of fallen *débris*.

In the old world we are accustomed to regard volcanoes as mainly responsible for the discharge of material and the building up of cones and deposits of lava and tuff, but in the new world, and especially in the Pacific, the geologists are accustomed equally naturally to invoke the agency of subsidence as the cause of any otherwise inexplicable hollow. During a recent visit there I took the opportunity of examining as many as possible of such real or supposed subsidences, and I select for our present discussion some of the most characteristic.

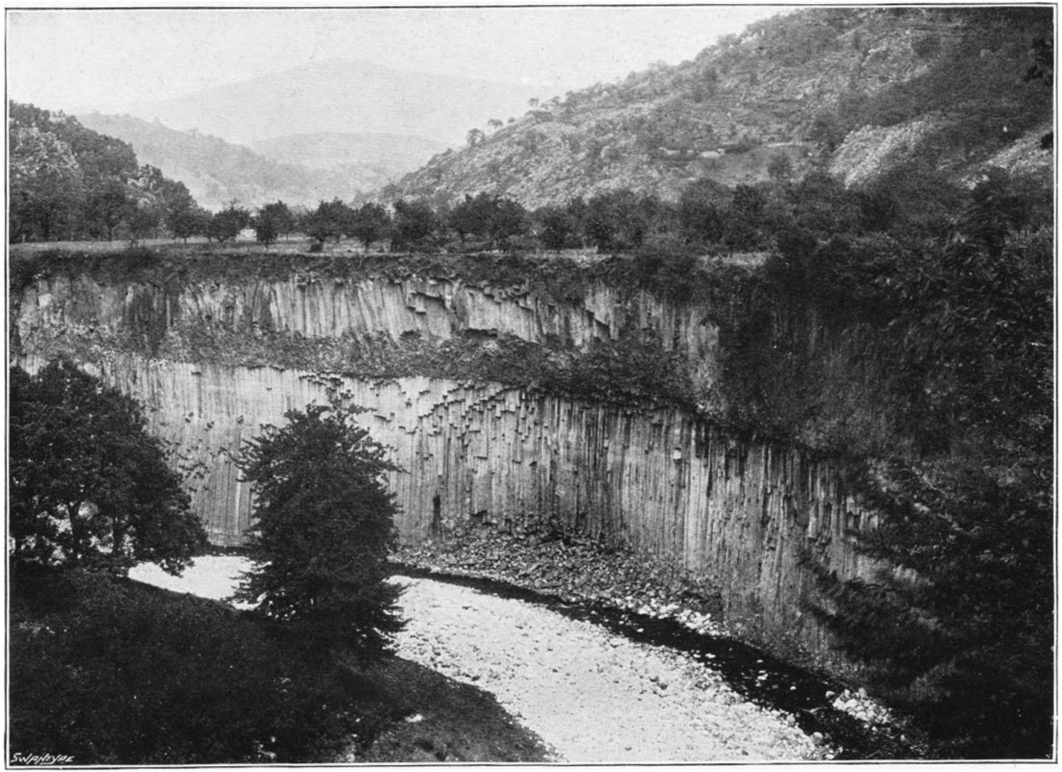
In an ordinary explosion crater, towards the waning of the eruption, there is often deposited a large bulk of material containing clay and various sulphur compounds. The gases which rise from the vent during the solfatara stages often also contain sulphur compounds. These, by contact with the air, tend to become oxydized into sulphuric acid, which, combining with the alumina of the clay, forms alum. Water percolating through this dissolves and removes the alum, and subsidence of the surface takes place. Such undoubted subsidences vary in area from the size of an ordinary sitting-room to several acres. Many such subsidences are found in the volcanic district of New Zealand, as at Waiotapu,† Roto Kawa, and Wairakei,† and of the reality of the cause in their cases I feel no doubt, but it is more difficult to accept it when a lake several miles in diameter is under consideration, and where no remains of alum beds are visible.

The great volcano of Kilauea in Hawaii, or Owyhee as it used to be called, is a good example of the type of effusive volcanoes as they occur in the Pacific, and its crater is often quoted as an example of a subsidence. The lava discharged from it is so fluid that the slope of the outside of the cone is only 5° or 6°, and in places I believe as low as 2°, so that the crater appears to be more a hole in a plain than in the top of a mountain, while

† Slide shown.



MONT PELÉE IN ERUPTION. A FORM OF VULCANIAN EXPLOSION.



ROCHER ST. MICHEL LE PUY, CENTRAL FRANCE. VOLCANIC NECK.

From Tempest Anderson's ' Volcanic Studies.' Murray.)

SCORIACEOUS LAVA OF 1886, NEAR NICOLOSI, ÆTNA.

DETAIL OF A LAVA-STREAM IN THE FOSSA VETRANA, VESUVIUS. CORDED LAVA IN FOREGROUND.

(*From Tempest Anderson's 'Volcanic Studies.' Murray.*)

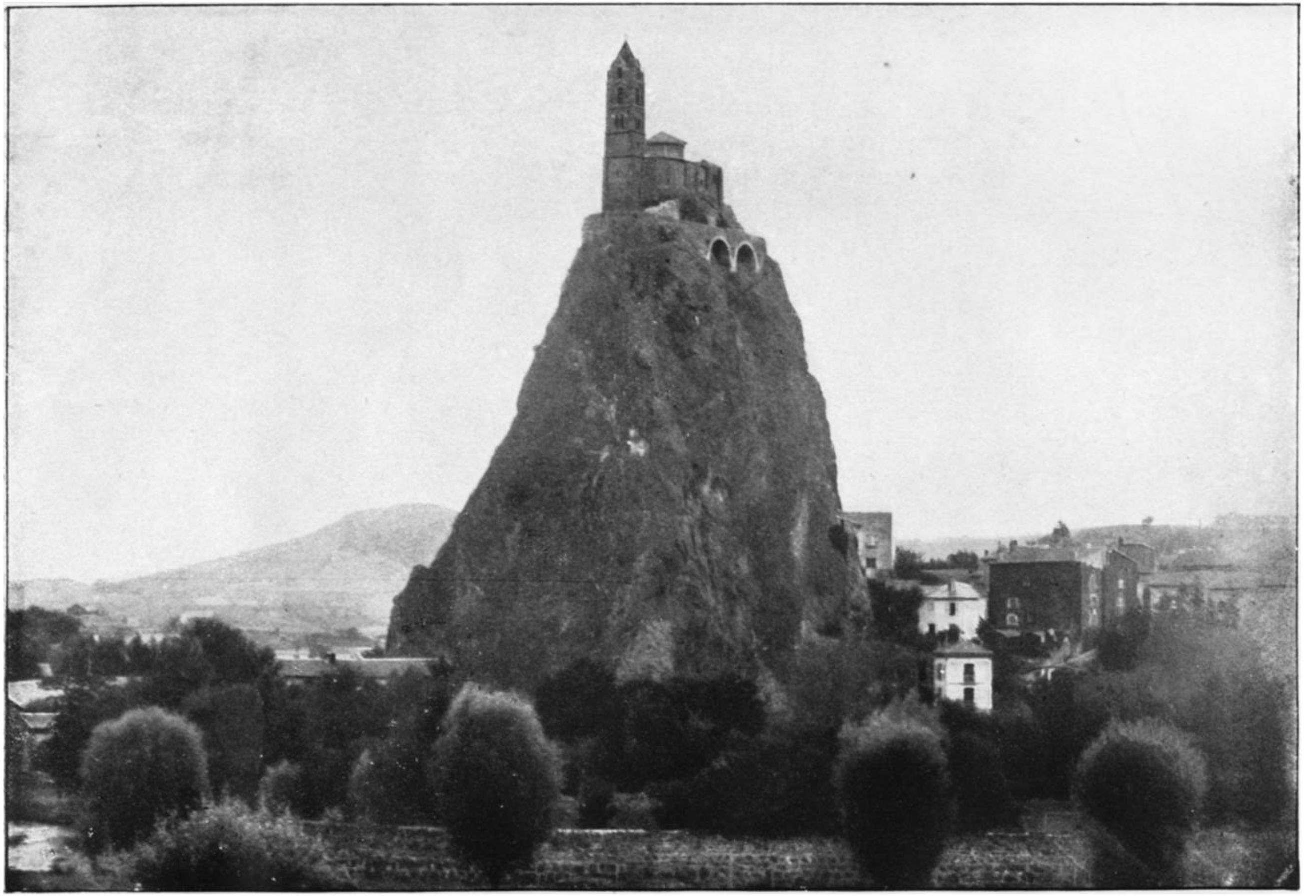
there is singularly little evidence of explosive action, such as the presence of ash, lapilli, or ejected bombs, all of which are very infrequent even right up to the brink of the crater. The details of its structure were shown by the aid of a series of photographs taken during a month's stay at the volcano house. These showed among other things the lake of liquid lava, partly crusted over, and with the crust broken up by a series of cracks, through which the red-hot molten lava was visible at dusk, and which were photographed by their own light, as was Old Faithful, the great fountain of molten lava, which usually plays at intervals about once a minute or oftener. Bays were also formed in the crater during this visit by the remelting of parts of the black ledge † of lava. They were comparable in size to the quadrangle of Burlington House, and the lava which was remelted was entirely removed.

Matavanu is a new volcano in Savaii, an island in the Samoan group, which only came into existence in 1905. Its crater † contains a lake, or rather river, of molten lava, comparable to, but more active than, that of Kilauea. The incandescent lava is so hot as to appear white-hot, even in tropical sunlight, so fluid as to rise in fountains more active than those in Kilauea, and to break in waves on the walls of the crater. Finally, the lava rushes with the velocity of a cataract into a tunnel, or rather gulf, at one end of the crater, where it disappears and runs underground under the crust of a large lava-field † for a distance of 10 miles to the sea, into which it falls with tremendous explosions.† Its course under the lava-field is marked by a number of large pits or fumaroles,† which appear to have been formed by the remelting and falling in of the crust over the tunnel. They are very similar in structure † to the pit craters of Hawaii,† the origin of which has given rise to so much discussion, and which were possibly formed in a similar manner.

As the lava at the seaside escapes from under the surface crust, it, where the action is not sufficient to set up explosions, begins to form lobes like those of ordinary corded lava †—and this corded structure is, in fact, formed in the usual manner in places above the water-level. Where, however, it falls direct into the sea, the surface is chilled before there is time for it to be wrinkled up into the corded structure, and it becomes consolidated into the characteristic form of one variety of pillow-lava.† This mode of formation, though previously on other grounds suspected by geologists, was, it is believed, first actually watched by the author in 1909.

The President (before the paper): The reader of the paper to-night, Dr. Tempest Anderson, bears a name well-known to geographers. Many of you here present are familiar with the work he has accomplished in connection with some of the greatest volcanoes in the world, and with the magnificent photographs with which, when he lectures to us, he illustrates their activity, and the effect exercised by them upon the surface of the globe, which is, of course, the main study for which geography exists. Eight years ago Dr. Tempest Anderson

† Slide shown.



ROCHER ST. MICHEL, LE PUY, CENTRAL FRANCE. VOLCANIC NECK.

(*From Tempest Anderson's 'Volcanic Studies.' Murray.*)

To replace plate of above title in Dr. Anderson's lecture in *Geographical Journal* of February, which ought to be labelled

LAVA FLOW, COLUMNAR BASALT, JAUJAC ARDÈCHE.