41. *Geology and Petrography of Io-sima (Sulphur Island), Volcano Islands Group.*

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Introduction.

Io-sima, situated 24°47′N. and 141°18′E., or Naka Io-sima, as it is frequently called to distinguish it from Kita Io-sima (San Alessandro I.) and Minami Io-sima (San Augustino I.), is a volcanic island entirely composed of andesitic rocks showing a distinct alkalic tendency. Although his opportunity in 1935 of studying this island was restricted to only four day's of field-work, the writer succeeded in obtaining some critical data concerning the geologic structure and rocks of this island, which will now be described in some detail.

Morphology.

In outline, Io-sima, which is the largest of the Volcano Islands group, is quite unlike the circular or elliptical form of the lesser ones (Kita Io-sima and Minami Io-sima) of the group. It has the form of a gourd with its neck at the S. W. end, with a SW.-NE. length of about 8 km and widths of from 1000 m to 4 km. As viewed from the sea it has the appearance usual to flat-topped islands of raised coral reefs, although its SW. end rises as a conical hill above the adjoining flat ground. The submarine topography roundabout suggests that the island represents the supermarine part of a large and flat dome-shaped swell that rests, in common with the lesser islands of the group, on a submarine ridge which, lying about 1000 m below the sea, separates the deep trough on the east of the island from the deep on the west.

Morphologically, the island may be divided into three parts: Motoyama, Suribatiyama, and Tidorigahara.

1. Motoyama. Occupying the NE. half of the island, Motoyama is a flat-topped, dome-shaped hill rising at its central part to a height 116 m above the sea. It is surrounded by vertical sea-cliffs on all sides, except at its SW. side where it is connected by a flat (Tidori-

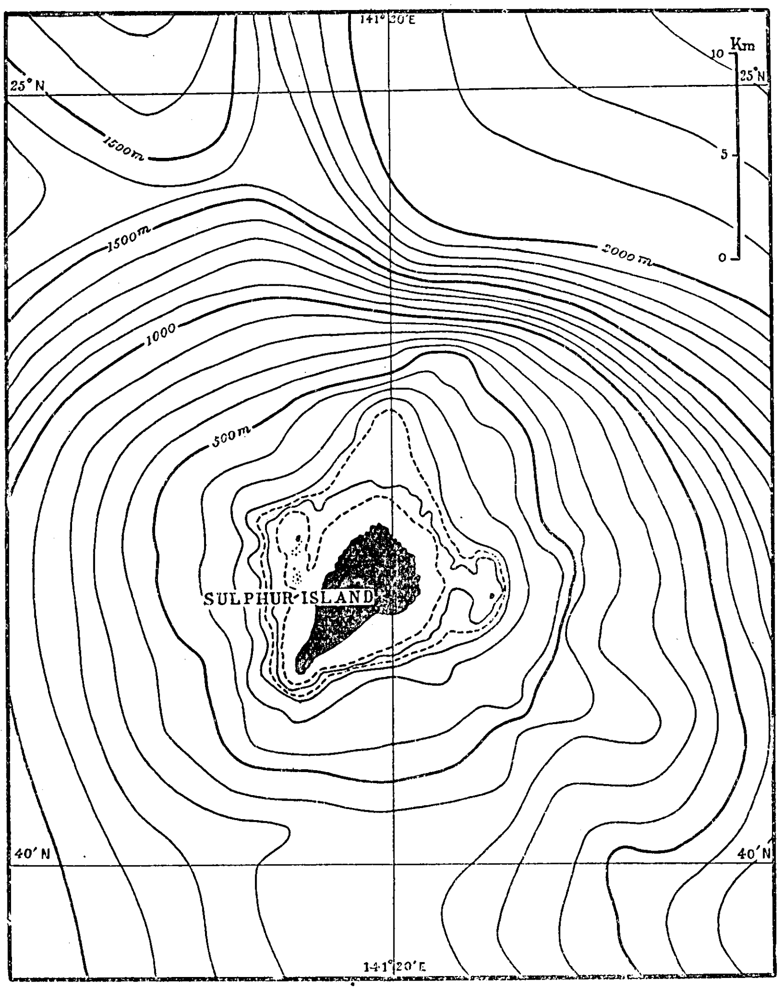

Fig. 1. Position of Sulphur Island in relation to the submarine areas about it. (Based on the chart, No. 50, of the Hydrographic Office, Imperial Japanese Navy).

gahara) with Suribatiyama. The sea-cliffs around Motoyama enclose flat coastal terraces that rise 5~10 m above the sea and generally terminate abruptly inland in cliffs. These inland cllifs again enclose a series of higher inland terraces that are completely separated from the present sea. The inland terraces are displayed most magnificently on the N. and NE. sides of Motoyama, where they rise one above another up to the summit, being bounded respectively by vertical cliffs, 5~20 m in height, each of which runs nearly parallel to the present coast. Thus the N. and NE. sides of Motoyama display as a whole a stepped topography. The S. side, where such inland terraces are generally absent, shows a gentle, uniformly curved slope. The SW. side descends gradually to the flat of Tidorigahara.

The terraces, with which Motoyama is surrounded, are undoubtedly uplifted wave-cut platforms, for not only are they planed across gently dipping strata of the tuff of which Motoyama is built, but they leave many traces of marine erosion. They are besides covered locally with thin beds of old beach-gravels and -sand; curiously curved rock-pinnacles are left on the terraces; while the inland cliffs, which represent old marine cliffs, are here and there deeply caved. The summit of Motoyama, wherein may be traced many marks of the marine erosion, is rough and rocky and traversed by fissure-like caves and depressions. Many reef-forming corals, which, according to T. Wakimizu[1], are of Recent and even of forms now living, are found preserved there in excellent condition.

From the foregoing facts it is evident that the terraces were formed during intermittent halts in a succession of uplifts to which Motoyama would have been subjected. Since the terraces grew outward through progressive uplifts, the highest one in the central part must be the oldest, the lower terraces having been formed successively later. It is thus quite likely that Motoyama was at first below sea level, and that its emergence occurred in recent geologic times, seeing that the reef-forming corals are preserved on the erosion relics above the oldest terrace. The first emergence of Motoyama and its succeeding stepwise uplifts can however be explained as the result of neither eustatic lowering of the sea nor regional crustal uplift. If the terraces were cut by successive lowering of the sea due to either of these causes, then equivalent terraces should probably be found on the adjacent shores. But seeing that none are found on the lesser islands of the Volcano group nor on the Bonin Islands, it seems necessary to invoke a more local cause than general crustal movement, and it is suggested that Motoyama emerged as the result of local upwarping of the sea-floor due to injection of magma that occurred as a cripto-volcanic phase in the course of the volcanic history of the island. Such an interpretation of the emergence of Motoyama is entitled to serious consideration, particularly as there are several additional factors in its favor, as will be mentioned presently.

2. *Suribatiyama* (Mt. Pipe). Suribatiyama is a truncated conical volcano with a base diameter of about 1km. At its summit is a funnel-shaped crater, roughly circular in outline and about 500 m in

1) T. Wakimizu, *Report Imp. Earthq. Inv. Comm.*, 56 (1906).

diameter. Nearly three parts of the crater-rim has an elevation of over 130 m, the highest point lying NE., where the rim reaches a height of 165 m above the sea. The crater-walls are very steep,

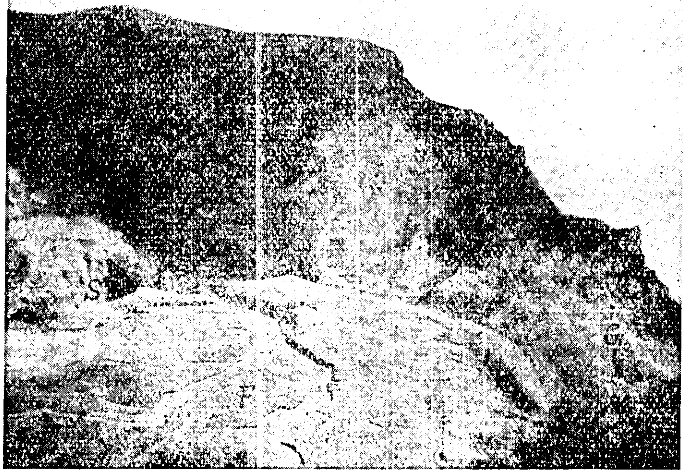

Fig. 2. The inside of the Suribatiyama crater, looking down from the NE. rim of the crater.
S: Solfataric pit, F: Crater-floor, G: Gap in the NW. crater-wall.

nearly vertical locally, although the W. wall is breached by a steep-walled gulch. The crater-bottom, which is circular in outline with a diameter of about 300 m, has a depth of about 100 m as measured at the highest point of the crater-rim. It is a flat ground covered with detritus from the surrounding walls, although it is marked by numerous branched stream-channels which converge to an axial channel that drains to the breach of the W. wall.

The outer flanks of the cone slopes at an angle of about 30° for only a little distance down the crater-rim, showing a natural slope of loose material ejected from the summit-crater, whence downward they form an almost vertical cliff with heights varying from over 100 m on the SW. side to 20 m on the NE. On the NE. side fronting the flat of Tidorigahara, the cliff is fringed along its base by an uplifted terrace, about 20 m high above the sea, while on the SW. side the much higher vertical cliff faces directly the present gravel beach without being fringed at its base by the uplifted terrace corresponding to that on the NE. side.

The vertical cliffs clearly represent old sea cliffs that have been cut away from the lower flanks of the cone by marine erosion at the time the sea stood 20 m or more above its present level, and when the cone was surrounded by that sea as an isolated insular volcano. Although the old sea cliff on the NE. side has undergone but little alteration since its position became out of reach of the waves, while that cn the SW. side has suffered severely from the prevailing wind and the consequent high waves from the southwest. The cliff on the SW. side has thus been excavated by the elements, showing many scars and slips, it being now higher than it was originally, its upper edge reaching a little below the crater-rim. The absence of the uplifted terrace on that side probably indicates that quarrying is more active than benching.

3. *Tidorigahara.* Tidorigahara, by means of which the preceding two parts of the island are connected with each other, is an elevated plateau land elongated in a NE.-SW. direction for a distance of about 2 km with breadths varying from 1000 m near Suribatiyama to 2 km at the opposit side. The SW. part of this area is about 40 m above the sea, and from this point the surface rises gradually to the northeast until it virtually reaches the summit of Motoyama. The NW. and SE. sides of the land, which for the most part show a gentle outward slope without any terraces or inland cliffs, are bounded respectively by extensive sand beaches extending in fairly straight lines for nearly 2·5 km between the cliffbound coasts of Suribatiyama and Motoyama.

A large part of Tidorigahara is veneered with drifting dune sand. Although some of the dunes are barchans of a more or less regular form, most are irregular heaps of sand, rather stable in position owing to the growth of grass and bushes. Between these heaps of sand are numerous conical depressions or holes varying up to a few meters in diameter, and arranged in lines running NE.-SW. Although some of them are decidedly solfataric, several traces of which remain thereabouts, most are of unknown origin. The system of holes and fissures indicates however possible lines of rupture along the longer axis of the island due to the upwarping to which the island has been subjected.

Geology.

Sulphur Island is formed entirely of volcanic rocks and their detritus, which the present study has shown to be separable from older to younger into the following seven formations.

1. Motoyama bluff tuff and Suribatiyama bluff tuff.
2. Motoyoma intrusive rock and Suribatiyama lava.

3. Suribatiyama cone ejecta.
4. Tidorigahara sand bed.
5. Terrace deposit.
6. Dune sand.
7. Beach deposit.

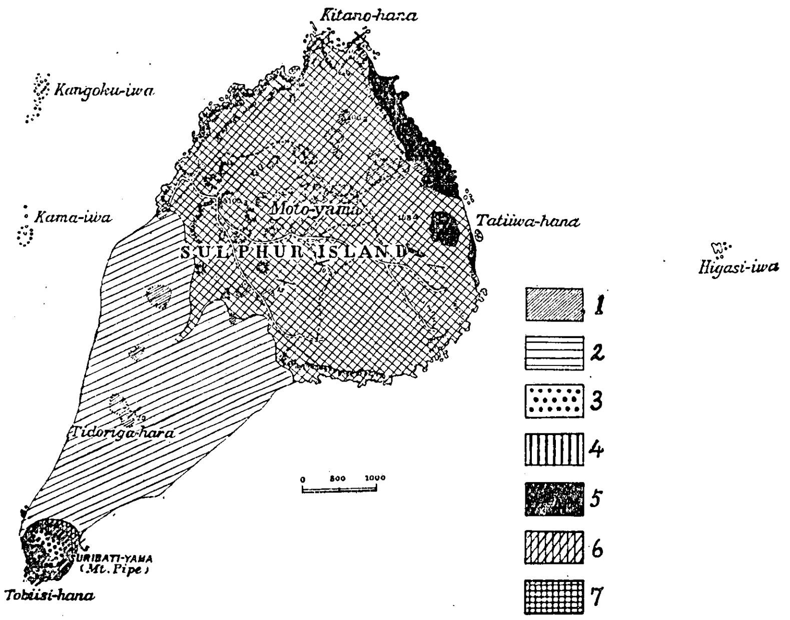

Fig. 3. Geological map of Sulphur Island; beach- and terrace-gravels, and dune-sand omitted.

1. Solfatara.
2. Tidorigahara sand bed.
3. Suribatiyama cone ejecta.
4. Suribatiyama.
5. Motoyama intrusive.
6. Suribatiyama tuff.
7. Motoyama tuff.

1. Motoyama Bluff Tuff. The oldest formation in the island, which the writer calls Motoyama bluff tuff, because its outcrops are characteristically bounded by bluffs (sea- and inland-cliffs), forms the greater part of Motoyama. Stratification is evident, though usually of a rude kind, showing gentle dips, mostly up to 15°, which radiate in all direction from the northeast-side part of Motoyama as the centre.

The tuff is divisible roughly into two horizons, according to the size of material of which it is composed. The upper horizon is represented by a yellowish-gray, fine, pumiceous tuff, occasionally interstratified with sandy tuff or tuff-breccia. Being covered locally with terrace deposit and blown sand, it is distributed widely and continuously not only in the central part, but on both the northern and southern sides of Motoyama. On the southern side, where the uplifted coastal terraces are generally absent, strata of fine pumiceous tuff occur continuously from central Motoyama downward and sink on the southern shore below the sea. They show a gentle southward dip coinciding with the surface slope of that side. On the northern side, however, the northwardly dipping strata are cut into vertical cliffs at the edges of the step-like uplifted terraces that are planed across the strata.

The lower horizon of the bluff tuff is represented by a pyroclastic accumulation, the greater part of which may fairly be termed obsidian agglomerate. It forms the lower parts of the inland- and sea-cliffs on the northeast side of Motoyama, and is intruded by the Motoyama intrusive to be described later. It contains abundant lava pieces, mostly of obsidian form, varying up to about 1 m in diameter. Bedding is more or less evident in the finer part of the accumulation; and even in the coarser, stratification of a kind is apparent in the distribution of the enclosed blocks.

The Motoyama bluff tuff is wholly volcanic, consisting exclusively of trachytic materials. Neither detrital material from an adjoining shore nor fossil has beed observed in it. But it is quite likely that the tuff is a product of submarine eruptions. T. Wakimizu[2], who visited the island in 1905 on his way to explore the ephemeral volcanic island that formed in 1904 near Minami Io-sima, suggested that Motoyama itself is a dome-shaped tuff-volcano that emerged in very recent geologic time. Although there seems to be little doubt that the tuff is of recent geologic age, his suggestion that Motoyama itself represents a tuff volcano is unacceptable to the writer, for if such were the case, then it should have its crater. No topographic feature of the summit of Motoyama gives any proof of the former existence of a central crater from which the materials composing the tuff would have been ejected, nor is there any such regular disposition of materials in the tuff as to suggest that the materials had been ejected radially from the summit of Motoyama as the centre. T. Tsujimura's opinion[3] with respect to the morphological aspect of the island is that Motoyama may be a dome that resulted from upwarping of the tuff. This is the conclusion the writer arrived at independently and which he sets forth in this paper, namely, that after being deposited nearly horizontally on the sea-floor at the time of its ejection from a submarine volcano, the tuff had been upwarped and placed in the

2) T. Wakimizu, *loc. cit.*

3) T. Tsujimura, *Jour. Geol. Soc., Tokyo*, 24 (1917).

present position. The occurrence of a trachytic intrusive into the tuff at Motoyama may be taken as indicating the probability of a genetic connection between its intrusion and the upwarping of the tuff.

Suribatiyama Bluff Tuff. Along the NE. coast of Suribatiyama for a distance of about 200 m southward from the SE. corner of Tidorigahara, occurs a series of rudely stratified agglomerate and sandy tuff, which the writer calls the Suribatiyama bluff tuff. In the whole northern half of the coast it forms a raised wave-cut terrace, about 20 m high, veneered with a terrace deposit; while in the south, where the terrace has entirely been eroded away by the quarrying action of the waves, it is exposed near the base of the precipitous cliff, being overlain by the Suribatiyama lava to be described later. The tuff thus represents the oldest formation visible of Suribatiyama. Its strata as a whole show a gentle southeastward dip. The sandy part of the strata is composed of small fragments of pumice and obsidian, together with isolated feldspar crystals, while the agglomeratic part contains angular blocks, up to 1 m in diameter, of obsidian, pumice, and compact lava of trachytic nature.

The direct stratigraphical relation between the tuff and the Motoyama bluff tuff is veiled by the Tidorigahara sand bed which separates the exposure of the one from that of the other. Y. Kikuchi[4], who visited the island in 1887 first as geologist, regarded the tuff under discussion as representing an outlier of the Motoyama tuff. The writer also believes that the Suribatiyama bluff tuff as a whole may probably be correlated with the lower horizon of the Motoyama bluff tuff formation. The close resemblance, structural as well as petrographical, between them suggests that they are the products of submarine eruptions from one or more than one source during the same age, although there is no definite evidence of this age, and that they join each other at the base of the Tidorigahara sand bed.

2. Motoyama Intrusive Rock. This mass, which is exposed patchwise at and near the NE. shore of Motoyama, extends along the shore southeastward for a distance of about 3 km from the northern promontory (Kitano-hana). Although this body has been neglected by many geological visitors to the island, its occurrence was noted by F. Homma[5], who, in an account of his tour to the Bonin Islands, wrote on the geology of the island with brief petrographic descriptions. He regards the mass as a lava-flow associated with th Moto-

4) Y. KIKUCHI, *Toyo Gakugei Zassi*, **5** (1888).

5) F. HOMMA, *Tikyu* (*the Globe*), **4** (1925).

yama tuff, and in his geologic map, indicates only about a half of its actual distribution. The writer however finds that the mass occurs as an intrusive into the Motoyama tuff instead of as a lava-flow. At the middle part of the north-eastern shore, where a rocky coastal terrace rises about 15 m above the sea, there is a good outcrop on the face of the sea-cliff that shows the actual mode of occurrence of the intrusive mass, as diagrammatically illustrated in Fig. 4.

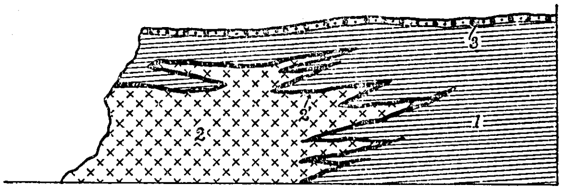

Fig. 4. Diagrammatic sketch showing the exposure in a sea-cliff on the NE. coast (Fig. 5.). 1: Motoyama tuff. 2: Motoyama intrusive, 2′: Quenched marginal facies (obsidian) of the Motoyama intrusive, 3: Terrace deposit (gravel and sand).

The sea-cliff, which represents a natural profile of the coastal terrace, consists of a rudely stratified sandy tuff or tuff-breccia and a massive trachytic rock, both of which are covered unconformably with a thin bed of terrace-gravels. The main mass of the trachytic rock has cut the tuff bed vertically, and several wedge-shaped offshoots of the former, 0·5∼1 m in thickness, have intruded laterally into the latter to about 5 m. The offshoots have well-defined walls exhibiting a pitch-black quenched border against the tuff into which they have intruded. It is possible that the intrusive had some effect on the structure of the adjoining tuff, seeing that the latter near its contact with the former displays an irregularly bent stratification.

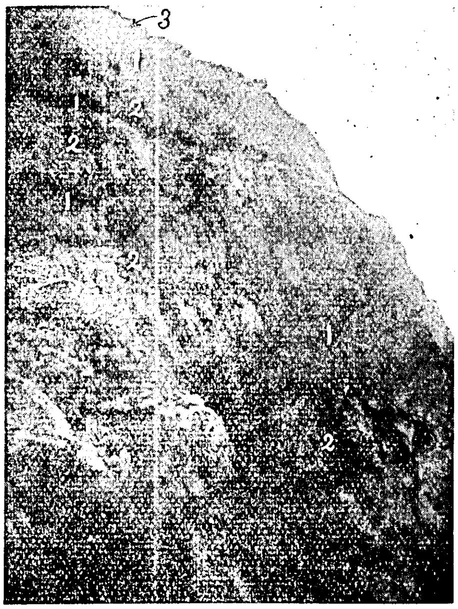

Fig. 5. Motoyama intrusive exposed in a sea-cliff on the NE. coast. (Fig. 4.)

A similar intrusive relation between the trachytic rock and the Motoyama tuff may be seen at a number of points in the inland-cliffs about 500 m south of the last-mentioned outcrop. The strata of tuff show an inclination entirely independent of the intrusive rock exposed, the former being traversed by the latter with highly inclined or quasi-vertical walls, although the very contacts between them have generally become indistinct as the result of decomposition due to the solfataric gases that frequently have their outlets on or near the contacts.

About 1000 m inland from the eastern shore is an exposure of the intrusive about 70 m above the sea, the highest exposure of the mass so far observed. This mass forms a sheet, less than 1 m in thickness, with a southward dip of about 35°. Its floor is an agglomeratic tuff representing the lower horizon of the Motayama tuff. Although the roof-rock is not exposed in contact with the sheet, it may be that it is represented by the fine pumiceous tuff that is exposed about 300 m seaward from the latter, the dip and strike of which are 35° S. and E.-W. respectively. The steep dip of the roof-rock, which is never found elsewhere, may be explained as a local effect caused by intrusion of the sheet rock.

Besides the exposures above described, the intrusive rock is exposed at several places on the uplifted terraces along the northeastern shore as erosion-relics projected above the flat surface of the latter, although its intrusion structures are veneered with the terrace deposit.

Petrographical characters of the intrusive mass are fairly uniform throughout all the exposures, suggesting that the exposed parts of the intrusive may be the apophysal border facies of a more extensive and continuous mass underlying a large area of Motoyama where it does not reach the present surface. It is inferred from the dome-shaped structure of the Motoyama tuff that, at a moderate depth beneath Motoyama, the continuous intrusive mass oocurs in the nature of a laccolith, and that the intrusion of this buried laccolith caused the dome-like upwarping of Motoyama. If that is the case, the exposed intrusive body seems to be offshoots insinuated through ruptures in the roof (the upper horizon of the Motoyama tuff) of this supposed laccolith at the time of its intrusion.

Suribatiyama Lava. This mass is exposed in the old sea-cliffs around Suribatiyama, forming a lava-flow about 20 m thick. It does not show a quaquaversal dip from the summit crater of Suribatiyama as the centre, but slopes gradually southwestward from the northeastern side of the volcano, where it rises about 40 m above the sea up to the upper edge of the old sea-cliff, to the rear where it descends to near the base of the cliff, beyond which the lava is buried beneath the beach gravels. Although S. Kozu and M. Watanabe[6] mention that

6) S. KOZU and M. WATANABE, *Proc. 3rd. Pan-Pacific Sci. Congr. Tokyo*, **1** (1926).

Fig. 6. Diagrammatic section of Suribatiyama from SW. to NE.

1. Suribatiyama tuff.	2. Suribatiyama lava.
3. Suribatiyama cone ejecta.	4. Tidorigahara sand bed.
5. Terrace gravel.	6. Dune sand.
7. Beach gravel.	S'. Solfatara.

"the cone is formed of the different layers of lava-flows", no lava-flows, except the present one, are actually observed.

The lava overlies disconformably the Suribatiyama bluff tuff. Near the contact with the latter the lava develops as a glassy, more or less vesicular form, while its inner part is uniformly and highly

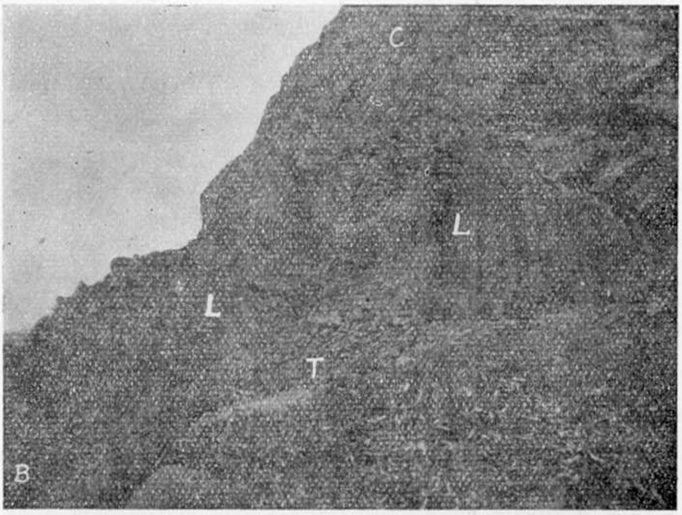

Fig. 7. The lower part of the E. slope of Suribatiyama.
B: Beach gravel. C: Suribatiyama cone ejecta.
L: Suribatiyama lava. T: Terrace gravel.

crystalline with no sign of flow structure, but displaying gross columner jointing. The roof-rock of the lava is not uniform throughout; on the southwest side it is represented by an accumulation of angular lava blocks or a breccia, and on the northeast, by a fine whitish tuff.

The extrusion of the lava may be nearly contemporaneous with the intrusion of the Motoyama intrusive. Although there is no structural evidence that the extrusion took place at the present summit-crater of Suribatiyama, there is no reason to suppose that the lava has come from Motoyama as the centre. Therefore, even though the lava is not the product of the present Suribatiyama crater, it would have extruded through a conduit not far from the latter, whence it is possible to regard the Motoyama intrusive as having been injected satellitically from this conduit at a moderate depth. Whether the postulated conduit lies beneath Suribatiyama or not, the Suribatiyama lava for the most part would primarily be below the sea, seeing that the overlying whitish tuff seems to be a submarine deposit.

3. *Suribatiyama Cone Ejecta.* The Suribatiyama cone ejecta have accumulated as well-defined strata forming the conical part of the whole upper half of Suribatiyama. These strata for the most part, except the lowest one, fall outward with dips varying up to 35° from the summit-crater of the cone as the centre. The lowest bed, so far as observed on the northeast flank of the cone, is the whitish tuff which, as noted above, seems to be a submarine deposit, while on the southwest flank it is represented by an agglomerate consisting of

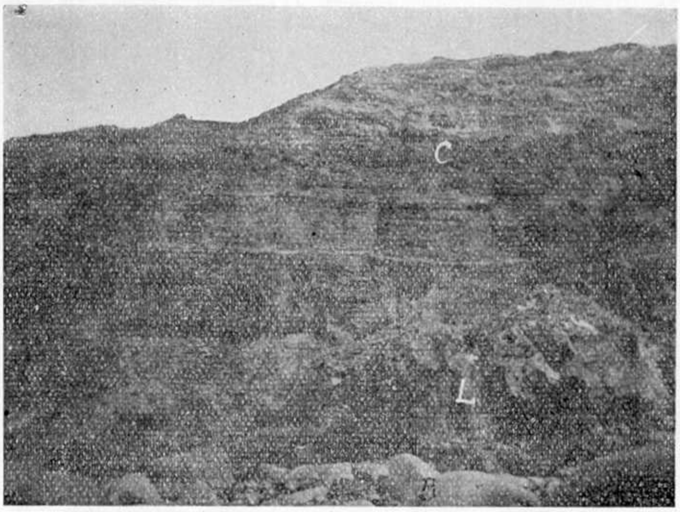

Fig. 8. The SE. slope of Suribatiyama, looking up from the SE. coast.
B: Beach gravel C: Suribatiyama cone ejecta
L: Suribatiyama lava.

angular lava blocks and ash material. Then follow alternating beds of finer and coarser grayish tuff which are exposed not only half way down the lateral slopes, but as the northeast crater-rim. Next to these beds come massive or rudely stratified beds of black scoriae occupying the whole outer slope near the crater-rim. A few accessory ejecta, evidently signs of the last explosive activity of the volcano, are scattered over the black scoriae.

The steep quaquaversal dip of the strata is evidence that they were subaerially accumulated on the underlying Suribatiyama lava after the sea had dropped relatively from the old sea-cliff with which the lava is bounded. As will be discussed later, the eruptions from which the cone was formed, must have occurred shortly before or during the deposition of the Tidorigahara sand bed now to be described.

4. *Tidorigahara sand bed.* The extensive flat of Tidorigahara should not be interpreted as an abrasion platform of the Motoyama bluff tuff, but as being formed largely of a sand bed thinly veneered with dune sand, although the exposure of the sand bed is limited to a few points in Tidorigahara, where the overlying dune sand is removed by artificial cutting or by solfataric action.

The sand bed as a whole must not be confused with the bluff tuff. Neither must the former be confused with the dune sand, although the materials composing them are quite the same. Thus the sand bed is composed of sandy grains of trachytic rock (pumice, obsidian, compact lava, and isolated feldspar crystals) and tuff fragments. These materials, which are evidently water-worn, are consolidated as a more or less coherent bed displaying irregular stratification with a gentle dip to the southeast.

Although the very bottom of the sand bed has not yet been uncovered, it is highly probable that the bed rests on the bluff tuff with the Suribatiyama cone ejecta in between them, seeing that not a few blocks of these supposed bed-rocks, which may owe their origin to solfataric explosions of unknown date, lie scattered at and near the solfataras in the northeastern part of Tidorigahara. Since it is expected that the surface of the Motoyama tuff gradually descends from Motoyama to the bottom of Tidorigahara and joins a similar tuff at the base of Suribatiyama without any marked discontinuity between them, the thickness of the sand bed may be no more than 50 m.

Both structure and composition of the sand bed indicate that the materials composing it must have been derived at second hand from either Motoyama or Suribatiyama or from more than one such source in the neighbourhood. The limited distribution of the sand bed and the well-worn form of its material point to the probability that Sulphur Island, in the course of its emergence, passed an epoch when, while its northeastern and southwestern parts (Motoyama and Suribatiyama) had emerged, its central part (Tidorigahara) remained as a slightly submerged sea-floor, and that the materials derived from the emerged land parts were accumulated on the sea-floor between these lands as the Tidorigahara sand bed. Together with the farther uplifting of the land parts subsequent to its deposition, the sand bed must have emerged to the present position with a slight tilt southeast.

5. *Terrace Deposit.* The terrace deposit, which consists of gravels and sand, lies on the floors of the terraces that cut into the bed rocks of the island. Although the deposit is not uniformly distributed on the floor of each terrace, locally it attains a thickness of more than 1 m. Thus whereas the terraces are usually covered on their inland edges, where they abut against the old marine cliffs, with gravels and sand accumulated as old beach ridges more than 1 m in height, they are swept clear in places at or near their seaward edges.

The terrace deposit at the northeastern foot of Suribatiyama, which is more than 2 m thick, consists practically of lava cobbles and lava blocks up to 2 m diameter, derived from the lava-cliff above the terrace. On the northeastern side of Motoyama, the terrace deposit on the lower terraces are composed of gravels and sand derived from the underlying Motoyama tuff and trachytic intrusive rock, while that on the higher terraces including the summit part of Motoyama, where the bed rock is exclusively the tuff, consists wholly of gravels, together with sand of this rock. The tuff gravels show generally a disk-like form, mostly less than 50 cm diameter, and 5~10 cm thick, as the result of being easily stripped off as platy blocks along the plane of stratification of the rock.

6. *Dune Sand.* The surface of Tidorigahara is covered with loose sand no more than 1 m thick, although locally they form sand-drifts, several meters higher than the general surface. They consist of small fragments of trachytic rock, such as pumice, obsidian, scoriae, solid lava pieces, and isolated feldspar crystals, besides a few pebbles (5~10 cm dia.) of the same rock. Based on the observations of O. Warburg who, although not a geologist, writes on the geology of the island, J. Petersen[7] mentions the feldspar sand as having been derived from the Motoyama tuff. Wakimizu[8], who opposes Petersen's view, stresses the fact that the sand are volcanic material ejected from Suribatiyama during its eruptions. Wakimizu's view, however, does not appeal to the writer for several reasons. If the sand were ejected from Suribatiyama, similar sand ought to have been found on its outer flanks. They bear no physical resemblance to the ejecta on Suribatiyama, although petrographically both are of the same tra-

7) J. PETERSEN, Beiträge zur Petrographie von Sulphur Island, Peel Island, Hachijo and Miyakeshima. (1890).

8) T. WAKIMIZU, *loc. cit.*

chytic character. The isolated feldspar crystals which amount to about 85% of the sand, are rounded off their face angles, occasionally showing a perfectly rounded shape. The rest of the sand, together with additional large pebbles, are likewise rounded. Thus most of the sand are evidently water-worn, although their rounded forms might be the result of wind-abrasion that gave rise to the three-facetted stones that one meets with although rarely among them. Some of the pebbles moreover are of fine pumiceous tuff similar to the Motoyama tuff. It is therefore highly probable that, while one part of the sand is blown sand drifted from the shores by the wind, the other has been derived from the loosely-coherent sand bed underlying Tidorigahara.

7. *Beach Deposit.* The beach deposit, which is the youngest formation of the island, consists of gravels and sand besides a few remains of the living marine shells piled up on the shores by winds and storms. The beach gravels are well developed along the shores of both Motoyama and Suribatiyama, where the sea-cliffs above the shores are being attacked by the waves, while the beach sand are practically confined to both shores of Tidorigahara. The gravels and sand are lithologically similar to the terrace deposit already described.

Solfataras.

Sulphur Island has more than twenty solfataras, some of which are emitting steam and sulphurous vapors, the column of steam being visible some distance out at sea. These solfataras are aligned on what may be two intersecting fissures; the Suribatiyama solfataras on the one and the Tidorigahara and Motoyama solfataras on the other.

The Suribatiyama solfataras are arranged on a fissure running in a NNW.-SSE. direction —the trend of the island-chain of the Volcano group— through a gap in the northwestern wall of the crater. The most active of them in 1935 was located at the southwestern corner of the crater-bottom, where sulphurous gases and vapor were issuing with a hissing noise from a circular opening some 10 m in diameter. Rock decomposition due to solfataric action is complete at the surface where it adjoins the solfatara. Not only does it cover the bottom ground of the crater, but it extends to the outer slopes of the crater-wall. Thus the NW. and SE. slopes of the cone, where several solfataras, active and extinct, occur, have been similarly decomposed. An extinct solfatara marked by rock decomposition is located in an isolated position half way down the northeastern slope, where the cliff of the Suribatiyama lava has been reduced to a talus by means of which the sumnit is barely accessible. This solfatara, together with the Tidorigahara solfataras next to be described, lies on a what may be a fissure running from the summit of Suribatiyama to Motayama through Tidorigahara.

Although the Tidorigahara solfataras are for the most part extinct, in the same areas are many traces of their former activity. Thus the surface of areas containing the solfatara have not only been incrusted by salt patches, but reduced by the thermal action of the solfataras to a fine sticky mud which dries out and becomes baked into a thin crust. There are local fissures and depressions in some of these areas. It is possible that the ground material of these areas consisting of the Tidorigahara sand bed was slowly carried away by the ground water owing to disintegration under the influence of solfataric action, with

Fig. 9. Motoyama Solfatara.

the result that the ground was undermined and parts of the surface slumped in.

The Motoyama solfataras occur mostly in a zone extending north-east ward from the summit of Motoyama to the northeastern shore. The most active of them, in 1935, was situated at the summit, quantities of sulphurous vapors issuing from several orifices scattered over a large area. The ground forming the solfatara area, which is composed of Motoyama tuff, is much decomposed, the accumulation of incrusting salt being greater in this area than in any other. Thus sulphur deposits are now worked commercially, although still on a small scale. Near the northeastern shore, where, the trachytic intrusive is exposed in contact with the tuff, numerous solfataras are developed at or near the contact between these rocks. On the SE. and NW. sides of Motoyama are almost no sign of solfataric activity, past or present, although a few solfataras, which are submerged at high water, occur close to the beach on these sides. The suggestion therefore arises that the solfataric vapors rise from the buried intrusive mass through ruptures in its roof (Motoyama tuff).

The temperatures of the solfataras are not the same, and no doubt they change from time to time. A vapor jet from a solfatara at the

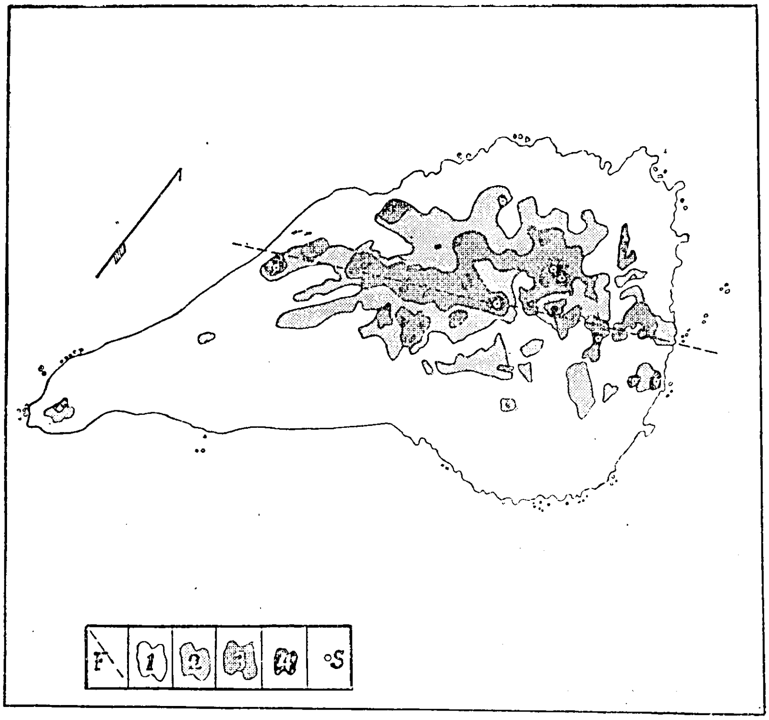

Fig. 10. Ground temperatures in Sulphur Island, May 1926. (After Toyoshima)

1: $<35°$C. 2: $\gtrless{}^{>35°}_{<60°}$C. 3: ${}^{>60°}_{<100°}$C. 4: $>100°$C.

S: Solfataras F: Possible centre-line of solfataric activity.

summit of Motoyama showed, in 1935, a temperature of 102°C. (atm. temp. 28°), while another one on the northeastern shore had a temperature of about 80°C. The ground in the immediate vicinity of the active solfataras are, naturally, unpleasantly hot and dry, even ground some distance away from the solfataras showing temperatures higher than that of the normal ground. Thus, according to Toyoshima's systematic survey[9] conducted in May, 1926, the ground temperatures in

9) J. Toyoshima, *Ringyo-siken-iho* (*Bull. Forestry Experim. St.*), **17** (1925).

the island 0·5 m below the surface were distributed as shown in Fig. 5.

Geological History.

From the foregoing descriptions, the geological history of Sulphur Island may be summarized as follows:

Whatever the history of the foundation may have been, there seems to be little doubt that the island is, geologically speaking, very recent. It first saw the light with the submarine explosive outbursts that gave rise to the Motoyama and Suribatiyama bluff tuffs. From a central vent, now represented by Suribatiyama, a submarine outflow of the Suribatiyama lava followed. Almost contemporaneously with the outflow began an injection of the Motoyama intrusive rock into the previously deposited Motoyama tuff. The intrusion, which might have originated satellitically at moderate depth from the conduit of the Suribatiyama lava, rose apparently through one or a number of fissures until it reached the lower horizon of the Motoyama tuff, where it spread laterally and upward with great force to form a laccomorphic mass. The beginning of the extensive uplift that brought the submarine Motoyama tuff above the sea and changed it into a dome of much the same form as we now see, appears to date back to the time of that intrusion. Thus as the intrusion advanced, the invaded strata of tuff gradually upwarped, while at the same time the ocean-bottom above the strata became shallower and shallower. Immediately before it emerged, its top should have been an ideal site for coral growth, forming a flat coral-covered summit of the submarine dome-shaped ridge.

By continued upwarping of the ocean-bottom, both the dome-shaped ridge of the Motoyama tuff and the neighbouring Motoyama lava rose above the water. But a small part between them, now represented by Tidorigahara, would have remained as a shallow sea. Thus, in its early stage, the present Sulphur Island consisted of a pair of smaller islands, Motoyama island and Suribatiyama island, separated by a shallow-water platform. These islands, as soon as they were formed, were attacked and reduced in size by marine erosion. The sandy material transported by the waves from the shores of these two supposed islands, were deposited on the shallow-sea platform as the Tidorigahara sand bed.

It was to the time of the deposition of the Tidorigahara sand bed that subaerial eruptions took place from a central crater, now represented by the Suribatiyama crater. The Suribatiyama cone ejecta are the products of these eruptions.

Together with the subsequent uplift of both Motoyama and Suribatiyama, Tidorigahara also emerged, the three parts having joined together into one island as we see at present. The uplif. of the island was not continuous, but occurred intermittently for a long period with frequent halts of the sea, during which intervals marine erosion was active on weaker rock like the Motoyama tuff, giving to the island its present terraced feature. Such stepwise uplift will be naturally expected, it being likely that the intrusion of the Motoyama intrusive rock occurred recurrently through a long period of time.

Motoyama tuff being a fairly homogeneous rock, one would expect the number of terraces to be fairly uniform throughout, even when due regard is had to varying conditions, such as protection by reefs and heavier erosion on windward shores; yet it is considerably greater at the northern and northeastern sides of Motoyama than it is elsewhere. This expressive development the writer considers to be due to a slight southward tilt to which the island was subjected in the course of its uplift. The Motoyama intrusive and the lower horizon of the Motoyama tuff are exposed only near the northeastern shore, where the uplift was relatively great. A number of the shoals and reefs off the northern and northeastern shores may be detached fragments of the tuff and/or the intrusive, which at one time would be exposed continuously and extensively outward from the shores.

As stated above, Sulphur Island and its adjoining sea-floor during a recent geologic age was an area of local but great crustal instability, beginning with a period of volcanic activity and continuing with a complex sequence of stepwise uplifts that involve frequent and sometimes great sudden changes of sea-level. Minor uplifts continued after that time, and is doing so to the present day. Thus, according to Homma, there are several places, now many meters inland from the sea, from which it was once possible to fish, or launch canoes, so that the island must be rising, although little is known regarding the actual rate of such rising.

There is no volcanic material that was ejected since the Suribati-yama cone ejecta had been formed, nor is there any historic record of an eruption in the island. But volcanic activity is manifested in the island even at the present day by numerous solfataras. One of these solfataras on the northwestern side of Motoyama is said to have culminated a few years ago in ejecting a small volume of solid material. It is also said that detonations are often heard from the sea northeast of the island.

Petrography.

A number of authors, who have written on the geology of Sulphur

Island, have also touched on its petrography. Thus Kikuchi[10] wrote of the Suribatiyama lava as basalt. Petersen[11] described several rock specimens collected by Warburg from the island as augite-andesite, and classified them as vitrophyric, pumiceous, and sulphur-bearing of its kind. Wakimizu[12] also defined the Suribatiyama lava as augite-andesite. The last two writers identified the feldspar phenocrysts in all the rocks of the island as an oligoclase. Later, Homma[13] adopted trachyandesite, instead of augite-andesite, as a preferable name for the Suribatiyama lava as well as for his "lava-flow" (the writer's Motoyama intrusive) exposed at Motoyama, citing in this connection the occurrence of not a few blocks of augite-syenite in the tuffs and terrace deposits. He identified the feldspar phenocrysts in the lavas and the isolated feldspar crystals in the Tidorigahara sand as an andesine—an identification to which the writer also arrived independently. Kozu and Watanabe[14] also refered the "lavas" of Suribatiyama to trachyandesite, and proposed a new name "Iwozimite" for these rocks, naming it afer the island.

As noted above, the rocks of the island, which could probably be determined only with difficulty from hasty observations, were defined in various way by different authors. So far as the writer's observations go, they may be called trachyandesite since they are close in petrographic characters, microscopical as well as chemical, to some trachytes of the Pacific islands rather than to the common Japanese pyroxene-andesites. This will be seen to be justified from the descriptions that follow.

1. Suribatiyama Lava (Crystalline olivine-augite-andesine-trachy-andesite).

This lava occurs as a massive flow, more than 20 m thick, forming the vertical cliffs that encircle Suribatiyama. Near its contact with the underlying tuff it exhibits a narrow platy parting parallel to the contact, while farther from the contact the parting gives place to hexagonal columnar jointing.

Megascopically, the rock is dense and more or less porphyritic with phenocrysts of feldspar, augite, and olivine, scattered through an aphanitic, but not glassy, groundmass. Although a more or less vesicular form is represented by an obsidian found near the contact with the underlying tuff, nowhere has a pumiceous facies been found. The

10) Y. KIKUCHI, *loc. cit.*
11) J. PETERSEN, *loc. cit.*
12) T. WAKIMIZU, *loc. cit.*
13) F. HOMMA, *loc. cit.*
14) S. KOZU and M. WATANABE, *loc. cit.*

color, except that of the pitch-black obsidian, is generally medium to dark gray with a greenish tint, while in a smaller number of specimens it is cream to light gray with pinkish tint, apparently due to incipient weathering, as seen in a specimen from the middle part of the lava-cliff on the NE. side of Suribatiyama.

Microscopically, no differences are observed in the specimen within the mass except the change in crystallinity of the groundmass from near where it has been in contact with the underlying tuff. Thus the rock, which is generally perpatic, consists of phenocrysts of plagioclase, augite, olivine, and subordinate magnetite and apatite, together with a groundmass which is either highly crystalline or more or less hyaline (Figs. 11, 12). The phenocrysts often form a glomeroporphyritic aggregate.

Phenocrysts: Plagioclase, which makes up the greater portion of the phenocrysts, is euhedral, some of them up to 5 mm in diameter, but often indented with inlets of the groundmass. It is simple or multiple-twinned in the usual way, rarely showing any twinning. Zonal structure is virtually absent save for a narrow clear border zone, although in a small number of crystals it is faintly exhibited near the border zone. Indices of refraction on (010) or (001) are $n_{1D}=1{\cdot}5493$, $n_{2D}=1{\cdot}5567$. Composition $Ab_{57}An_{43}$. The narrow clear border zone is an alkali feldspar (anorthoclase) having a lower refraction than Canada balsam and $2V=62°$, $49°$, or $46°$ $(-)$[15].

Augite is euhedral, $0{\cdot}5\sim3$ mm in diameter, and pale brownish without perceptible pleochroism. Zonal structure is faintly exhibited; the interior of each zonally-built crystal has $2V=55°(+)$, while the marginal zone $2V=48°(+)$. But some crystals, in which the zonal structure is inperceptible, have $2V=57°$, or $61°$ $(+)$. The refractive indices are larger in the intrior ($n_{1D}=1{\cdot}6974$) than in the marginal part. The approximate composition of the pyroxene is $Wo_{40}En_{37}Fs_{23}$, according to the Tomita Diagram[16].

Olivine is euhedral to rounded, up to 1 mm in diameter, and nearly colorless. It has $2V=84°(-)$ with $\beta_D=1{\cdot}7020$ corresponding to $Fo_{66}Fa_{34}$.

Magnetite, which is euhedral to anhedral and $0{\cdot}1\sim0{\cdot}3$ mm in diameter, occurs as isolated grains or in close association with augite and olivine.

15) The values of 2V for feldspar and mafic minerals were measured on the universal stage using hemispheres of refractive index 1·57 for feldspar and 1·649 for mafic minerals.

16) T. Tomita, *Jour.Shanghai Sci. Inst.*, 1 (1934).

Apatite, which is prismatic, up to 0·5 mm in length, and nearly colorless, occurs either as enclosures in phenocrysts of feldspar, augite, and olivine, or is dispersed as isolated crystals throughout the rock.

The phenocrysts in the obsidian near its contact with the underlying tuff are identical with those above-mentioned except the plagioclase which, in the obsidian, is not rimmed with alkali feldspar.

Groundmass: The groundmass of the Suribatiyama lava, except that of the contact facies, is highly crystalline, consisting of feldspar, pyroxene, hornblende, and iron-ore, with a texture that is not typically trachytic because of the predominance of equant anhedral feldspar.

Feldspar includes both plagioclase and alkali feldspar. The plagioclase, which occurs as prismoids measuring 0·1 mm and less in length, is multiple twinned in the usual way. It has $2V=82\sim86°(-)$ with $n_{1D}=1·5439$ corresponding to a calcic oligoclase $Ab_{72}An_{28}$, which is identical with the marginal part of the faintly zoned phenocrystic plagioclase. The alkali feldspar occurs either as euhedral thin laths (0·05 mm in length) or as anhedral crystals filling the interstices between other groundmass minerals. It also attaches to the margin of the plagioclase laths. The refractive indices are $\alpha_D=1·5253$, $\gamma_D=1·5325$. Zoning is observable in some of the larger crystals, in which the optic angle gradually decreases from the core toward the margin of each crystal; $2V=71°(-)$ in the core, and $2V=48°(-)$ in the margin. These optical characters are almost those of anorthoclase, corresponding to what attaches to the margin of the phenocrystic plagioclase.

The pyroxene, which is dispersed through the groundmass as minute grains (0·03 mm dia.) and prismoids (0·1 mm long), includes both pale brown augite and greenish alkali pyroxene. Besides occurring as isolated crystals of each pyroxene, they are combined as zoned crystals, in each of which the core is always represented by the augite and the margin by the alkali pyroxene. The boundary between the two pyroxenes is generally sharp, although there are some crystals in which the augite in the core gives way gradually outward to the alkali pyroxene of the margin. The augite has $n_{1D}=1·6997$, $2V=55°(+)$, and the extinction angle $c\wedge Z'=51·5°$(max.). The approximate composition is $Wo_{40}En_{36}Fs_{24}$. The alkali pyroxene shows distinctly but not strong pleochroism, X=pale green, Y=green, Z=greenish brown, with absorption $X>Y>Z$. Its refractive indices are higher than 1·750. $2V=68\sim73°(-)$. The optic plane is parallel to (010); the extinction angle $c\wedge X$ is very small or nearly zero. These optical characters indicate the alkali pyroxene to be an acmite[17].

17) Washington and Barth describe this mineral in a trachyte from the island of Hawaii. H. S. Washington, *Am. Jour. Sci.*, **23** (1923); T. W. Barth, *ibid.*, **31** (1931).

Hornblende, which occurs as minute laths and scraps, 0·05 mm in diameter, is deep brownish with distinct, but not strong, pleochroism, Z (or Y) = reddish brown, X = light greenish brown, and absorption Z (or Y) > X. The extinction angle $c \wedge Z'$ (max.) = 21°. $n_{1D} = 1{\cdot}6465$, $n_{2D} = 1{\cdot}6552$.

Chemical Composition: Chemical analyses of two specimens of the rocks from the islands were made by Petersen[18], of one by K. Yokoyama for S. Kozu[19], and of one by the Imp. Geol. Survey for D. Sato[20]. Unfortunately however, since the exact localities of the analyzed specimens are not mentioned by the respective analysts, it is uncertain which of these analyses is of the Suribatiyama lava under discussion. A new analysis was therefore made by S. Tanaka of a gray-colored highly crystalline specimen which the writer collected from the columnar lava exposed near the south coast (Tobiisi-hana) of Suribatiyama. Another new analysis was made also by Tanaka of a specimen from the Motoyama intrusive to be described later. These two new analyses are shown in Table I, in which the four old analyses are also given for comparison, together with three others — Homma's augite-syenite[21] from Sulphur Island, andesitic pumice[22] of the 1914 eruption from the submarine volcano near Minami Io-sima, and a trachyte from Hawaii.

The Suribatiyama lava is, like others from the island, decidedly high in alkalies, especially soda. Thus the normative plagioclase is an oligoclase $Ab_{84}An_{16}$. The normative pyroxene has the composition $Wo_{35}En_{39}Fs_{26}$ (Wt. %). The presence of a little quartz (excess silica) in the norm, although the rock carries silica mineral neither as phenocryst nor as a constituent of its crystalline groundmass may be ascribed to the assumption in calculating the norm. Some of the iron molecules which, in calculating the norm, are assigned to form magnetite, are believed to have primarily entered modal pyroxene and thus to have been combined with silica. As compared with the Motoyama intrusive, the only notable difference is in the ratios of the ferric and ferrous oxides, the differences between the amounts of the other constituents being quite insignificant. Assuming, therefore, that the iron oxides in the rock under consideration are 0·6% Fe_2O_3 and 4·6% FeO, which corresponds with the distribution in the analysis of the Motoyama intrusive, the norm shows 3·45% olivine instead of quartz.

18) J. PETERSEN, *loc. cit.*
19) H. S. WASHINGTON, *Chem. Anal. Ign. Rock*, (1917).
20) D. SATO, *Ganseki Tisitugaku*, (1925).
21) F. HOMMA, *loc. cit.*
22) T. WAKIMIZU, *Toyo-gakugei-zassi*, **37** (1919).

2. Motoyama Intrusive (Vitrophyric olivine-augite-andesine-trachyandesite).

This rock is exposed on the northeastern side of Motoyama as an intrusive into the Motoyama tuff. Megascopically it is various, as it exhibits every gradation between highly vitreous and more or less felsitic characters. Specimens from near its contact with the tuff are jet-black obsidian with sporadic phenocrysts of feldspar, augite, and olivine, while those from some distance away from the contact are pale to dark gray and contain phenocrysts of feldspar, augite, and olivine scattered through an aphanitic groundmass.

Microscopically, the rock carries a few phenocrysts of plagioclase (1∼5 mm dia.), augite (0·5∼1 mm) and olivine (0·5∼1 mm), with subordinate magnetite (0·5 mm) and apatite (0·5 mm long) in a glassy groundmass (Fig. 13.). The phenocryts often form a glomeroporphyritic aggregate (Fig. 14.).

Phenocrysts: Plagioclase has almost the same optical characters as that of the above-described rock; $n_{1D}=1{\cdot}5499$, $2V=83°(+)$, composition $Ab_{55}An_{45}$, but it is not rimmed with alkali feldspar.

Augite, which is pale brown without discernible pleochroism, is not zonally built; $n_{1D}=1{\cdot}6970$, $2V=54{\cdot}5°(+)$, composition $Wo_{40}En_{37}Fs_{23}$ (Wt. %).

Olivine, which is euhedral to rounded, has $2V\doteqdot 83°(-)$.

Groundmass: The groundmass of the obsidian consists wholly of a pale to dark brown glass of refractive index varying from 1·5237 to 1·5277 for Na light. Microscopic flow-banding is exhibited by color differences between the bands, which vary from faint to quite pronounced.

The groundmass of the felsitic specimen consists of feldspar microlites, pyroxene granules, and glass base filled with black dust material of what appears to be magnetite. The feldspar microlites are for the most part an alkali feldspar of refractive indices less than Canada balsam. The pyroxene granules are greenish with distinct pleochroism suggestive of an alkali pyroxene. But these minerals are so small that no satisfactory determinations of optical properties could be made. They are crowded in microscopic bands exhibiting sinuous flow lines.

Chemical Composition: A specimen of the Motoyama intrusive at the exposure illustrated in Fig. 5 was chemically analyzed with the result given in (II) of Table I. Chemically the rock resembles the Suribatiyama lava, although microscopically the former is more hyaline than the latter; the normative plagioclase is an oligoclase $Ab_{89}An_{11}$. The only notable difference between them is in the ratios of the iron

Table I.

	I	II	III	IV	V	VI	VII	VIII	IX
SiO_2	58·91	59·60	59·30	60·32	59·87	61·28	60·55	60·82	62·02
Al_2O_3	17·71	16·81	16·61	16·09	17·23	18·16	17·29	16·63	18·71
Fe_2O_3	2·81	0·83	1·51	4·88	9·96	5·97	2·72	1·15	4·30
FeO	2·67	5·87	5·02	3·04	nd.	1·76	3·22	3·46	0·10
MgO	0·88	1·34	1·55	1·34	0.77	0·79	1·12	1·79	0·40
CaO	3·47	3·10	3·16	3·10	2·96	3,55	3·22	3·35	0·86
Na_2O	6·01	6·11	5·63	4·93	6·21	5·51	5·37	5·62	6·90
K_2O	3·94	4·17	4·41	3·90	2·92	2·75	4·36	4·21	4·93
H_2O +	0·34	0·25	0·95	} 0·65	} 0·61	} 1·72	0·53	1·84	0·80
H_2O −	0·30	0·10					0·21	(ign. 1)	0·31
TiO_2	0·82	0·86	1·11	0·66			0·85	0·45	0·31
P_2O_5	0·49	0·50	0·44	0·56			0·28	0·22	0·24
MnO	0·16	0·26	0·21	0·25			0·19	0·39	0·15
Total	100·23*	99·80	99·90	99·83			99·91	99·93	100·13⁑
Q	1·62	——	——				4·50	1·98	1·80
Or	23·37	24·49	26·16				25·60	25·04	28·91
Ab	50·83	51·91	47·71				45·62	47·71	58·16
An	9·74	6·12	6·95				10·29	7·51	2·22
Py wo	1·97	2·32	2·44				1·51	3·02	C 1·43
Py en	2·20	1·10	3·81				2·81	4·42	1·00
Py fs	1·45	3·43	6·59				2·64	5·27	
Ol fo	——	1·55	——				——	——	——
Ol fa	——	4·48	——				——	——	——
Mt	4·17	1·16	2·08				3·94	1·52	Hm 4·30
Il	1·52	1·67	2·12				1·67	0·91	0·15
Ap	0·99	1·32	0·99				0·65	0·65	0·67
									Ru 0·24
Norm plag.	Ab_{89} An_{16}	Ab_{89} An_{11}	Ab_{87} An_{13}				Ab_{82} An_{18}	Ab_{86} An_{14}	Ab_{96} An_4

* includes S=1·71; ⁑ includes ZrO_2=0·06, SO_3=0·02, BaO=0·02.

I. Olivine-augite-andesine-trachyandesite. Suribatiyama (Mt. Pipe), Io-sima (Su'phur Island). S. Tanaka, anal.

II. Olivine-augite-andesine-trachyandesite. Motoyama, Iô-sima. S. Tanaka, anal.

III. "Oligoclase-andesite". Io-sima. K. Yokoyama, anal.

IV. "Pyroxene-andesite", Io-sima. Imp. Geol. Survey, anal.

V., VI. "Augite-andesite". Io-sima. J. Petersen, anal.

VII. Augite-syenite. Io-sima. Ushijima, anal.

VIII. Olivine-pyroxene-andesite. Pumice of 1914 eruption, "Sin Io-sima" (New Sulphur Island). Imp. Geol. Survey, anal.

IX. Albite-trachyte. Puu Anahulu near Hualalai, Hawaii. H. S. Washington, anal.

oxides. With almost the same total amount of iron (reduced to either oxide), the Motoyama intrusive contains much more ferrous and less ferric oxide, while the Suribatiyama lava has more ferric than ferrous oxide. Therefore, whereas the former has normative olivine, the latter carries normative quartz.

The old analyses (III, IV, V, and VI of Table I) of the rocks from the island are not seriously inconsistent, so far as the determinations go, with the new ones of the rocks above described. Although there are some differences in the rate of oxidation of the iron, the total amount of the iron oxide is about the same in each analysis. The close chemical resemblance betwen the two new analysis and also that between these two and the old analyses indicate the chemical definiteness of the rocks of the island. Thus these rocks differ greatly from the common pyroxene-andesites of the Huzi Volcanic Zone or the average Japanese andesite of Yamada, the differences being shown chiefly in the much higher alkalies, especially soda, with the consequent very sodic nature of the normative plagioclase, and also in the very small amount or entire absence of normative quartz of the former as contrasted with the latter.

The above-described rocks resemble, in chemical composition, the pumice (VIII of Table I) that was ejected in 1914 from the submarine volcano near Minami Iô-sima. They also resemble the trachytes from Hawaii, an analysis of which is given in IX of Table I.

3. Motoyama Tuff, Suribatiyama Ejecta, and Tidorigahara Sand.

There is no need to describe these rocks in detail here, as they arer composed of fragmentary material which, although of diverse appeaances such as pumiceous (Fig. 16.), vitreous, scoriaceous, and felsitic, are petrographically very similar to either the Suribatiyama lava or the Motoyama intrusive, as shown in the examples that follow.

Motoyama tuff: Plagioclase $Ab_{55}An_{45}-Ab_{60}An_{40}$ ($n_{1D}=1{\cdot}5512-1{\cdot}5475$).
Augite $n_{1D}=1{\cdot}6923-1{\cdot}6970$.
Olivine present.
Obsidian glass $n_D=1{\cdot}5210-1{\cdot}5260$.

Suribatiyama tuff: Plagioclase $Ab_{55}An_{45}-Ab_{58}An_{42}$ ($n_{1D}=1{\cdot}5512-1{\cdot}5489$).
Augite $n_{1D}=1{\cdot}6964-1{\cdot}6996$.
Olivine present,
Obsidian glass $n_D=1{\cdot}5201-1{\cdot}5253$. $n_D=1{\cdot}5332-1{\cdot}5370$.

Suribatiyama ejecta (scoriae): Plagioclase $Ab_{57}An_{43}$ ($n_{1D}=1{\cdot}5497$).

Tidorigahara sand: Plagioclase $Ab_{40}An_{60}-Ab_{60}An_{40}$ ($n_{1D}=1{\cdot}5596-1{\cdot}5475$).
Augite $n_{1D}=1{\cdot}6970$,
Obsidian glass $n_D=1{\cdot}5400-1{\cdot}5450$.

Homma mentions whitish holocrystalline blocks that lie scattered in the Motoyama tuff, terrace deposit, and in the Tidorigahara sand. According to him, they are of augite-syenite, consisting of anorthoclase ($\alpha_D \doteqdot 1{\cdot}530$), pale green augite, aegirine-augite, olivine, cataphorite (?), magnetite, and apatite, with a little interstitial glass; one of them having the composition shown in VII of Table I. A similar blook collected by the writer from the Tidorigahara sand is subangular, about 5 cm in diameter, and medium-grained with pyroxene, olivine, and obsidian glass in a whitish feldspathic ground. Microscopically it is a hypidiomorphic aggregate composed of plagioclase, alkali feldspar, monoclinic pyroxene olivine, magnetite, and apatite, with a little interstitial glass. (Fig. 15.). The plagioclase, which occurs only as the core of the alkali feldspar, is zonally built, with composition varying from $Ab_{76}An_{24}(n_{1D}=1{\cdot}5402)$ to $Ab_{83}An_{17}(n_{1D}=1{\cdot}5366)$. The alkali feldspar, which also shows zonal structure, has 2V $(\rho>v)=62°\sim55°$ in the core part and $2V=45°\sim40°(-)$ in the marginal part. The refractive indices are $\alpha_D=1{\cdot}5238-1{\cdot}5256$, $\gamma_D=1{\cdot}5316-1.5339$, corresponding to an anorthoclase. The monoclinic pyroxene is greenish brown without discernible pleochroism. Zonal structure is very faintly exhibited, the core part having $2V=59\sim60°(+)$ and the marigin $2V=55°(+)$. The refractive indices ($n_{1D}=1{\cdot}7014$) indicate an augite rather rich in iron. Olivine, which is subordinate in amount, is pale yellowish green and has $2V=68°(-)$. Much of isometric magnetite and prismatic colorless apatite are enclosed in the feldspar and augite crystals. The interstitial glass is pale greenish brown with $n_D=1{\cdot}5117-1{\cdot}5170$.

Although the crystalline block was not chemically analyzed, it is expected from its mode that it may be chemically almost equivalent to the Suribatiyama lava and Motoyama intrusive. Homma's augite syenite is indeed chemically similar to these rocks.

The crystalline blocks cannot be regarded as having been derived from secretionary patches in either the Suribatiyama lava or the Motoyama intrusive, if patches there had been. They are probably a plutonic equivalent of either the Suribatiyama lava or the Motoyama intrusive. which, although not exposed at present, underlies the island, and which was thrown out as accessory ejecta during past volcanic eruptions of the island.

41. 火山列島硫黄島の地質及岩石に就いて

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硫黄島（俗稱中硫黄島）は北硫黄島と南硫黄島との略中間に位し，橄欖石・輝石・中性長石・粗面安山岩の熔岩，迸入岩，凝灰岩，砂礫等より成る火山島である．此島の大部分は最近の地質時代に活動した海底火山の隆起に依つて生じたもので，特に其北東過半部を占めてゐる元山の地質構造は嘗て海底に沈積した凝灰岩が粗面安山岩質岩漿の餅盤状淺處迸入に因つて圓頂丘狀に押し上げられた事を示してゐる．本文では同島の地形及び地質構造を述べ，其結果から島の發育の歴史を推定し，最後に同島を構成する岩石の顯微鏡的並びに化學的性質を記載した．

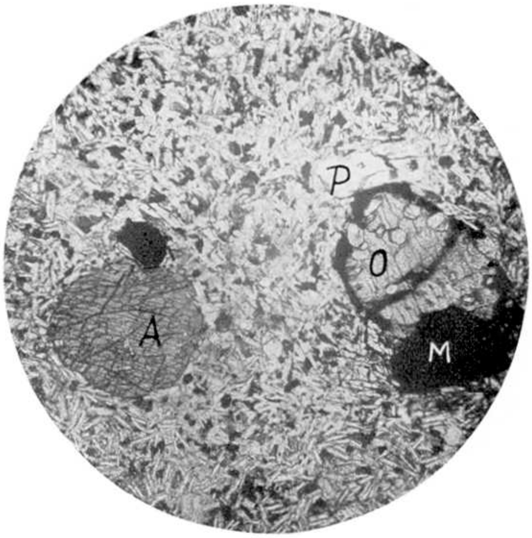

Fig. 11. Suribatiyama Lava (Crystalline olivine-augite andesine-trachyandesite). P: Andesine A: Augite O: Olivine M: Magnetite. ×32

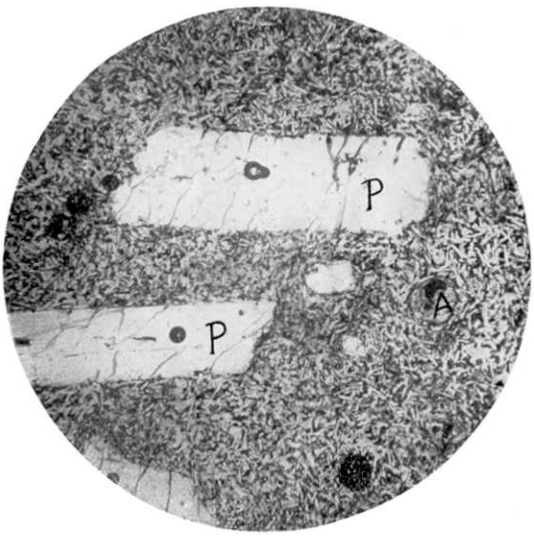

Fig. 12. Ditto. P: Andesine A: Augite ×30

Microphotographs of the Rocks of Sulphur Island.

Fig. 13. Motoyama intrusive (Glassy olivine-augite-andesine-trachyandesite). P: Andesine A: Augite ×21.

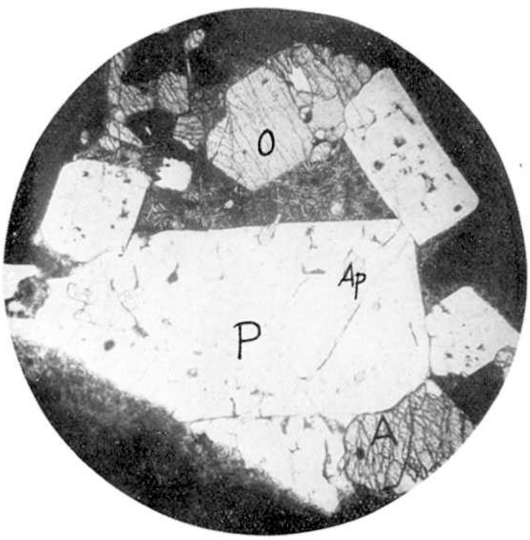

Fig. 14. Motoyama intrusive (Glomeroporphyritic aggregate of phenocrysts). P: Andesine O: Olivine A: Augite Ap: Apatite. ×30

Microphotographs of the Rocks of Sulphur Island.

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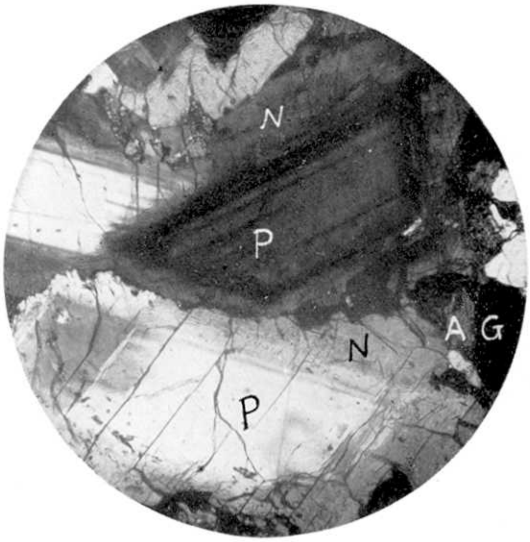

Fig. 15. Crystalline block (Crossed nicols). P: Oligoclase
N: Anorthoclase A: Augite G: Interstitial glass. ×21

Fig. 16. Motoyama tuff composed of microscopic fragments of pumice. ×30

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Microphotographs of the Rocks of Sulphur Island.