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FALCON ISLAND.*

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ABSTRACT.

Falcon Island, an active Tongan volcano, is described as a typical South Sea island in the making. It is a pyroclastic cone built by explosive eruptions. Eventually erosion will reduce it to a submarine bank which at a later date may be covered by limestone and uplifted. Many islands in the southwest Pacific have had such a history.

FOREWORD.

Falcon Island lies in the southwestern part of the Pacific Ocean, being a member of the Tongan Group. Its more exact location is about latitude 20 degrees 19 minutes South and longitude 175 degrees 25 minutes West. The island is of unusual interest because it represents the first of a series of evolutionary stages through which many South Sea islands have passed.

HISTORICAL ACCOUNT.

Falcon is a young island when compared to its neighbors but in spite of its youth it has had a somewhat varied history. First knowledge of its existence was received in 1865 when H. M. S. *Falcon* visited the site and reported a shoal. In 1877 H. M. S. *Sappho* observed smoke issuing from the sea at the same position. Eight years later a series of eruptions occurred which built a cone nearly 300 feet above sea level. This cone was composed of fragmental volcanic materials which were easily attacked by the agents of erosion. Thus, Lister reported[1] that in 1889 two-thirds of the original mound

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[1] Lister, J. J., A Visit to the Newly Emerged Falcon Island, Tonga Group, South Pacific, Proc. Royal Geog. Soc., 12, 157-160, 1890; and Notes on the Geology of the Tonga Islands, Quart. Jour. of the Geol. Soc. London, 47, 590-617, 1891. See also the following references: Wharton, W. J. L., Notes on a recent volcanic island in the Pacific, Nature, 41, 276-278, 1890. Phillips, Coleman, Volcanoes of the Pacific, Trans. and Proc. New Zealand Inst., 31, 512-515, 1898.

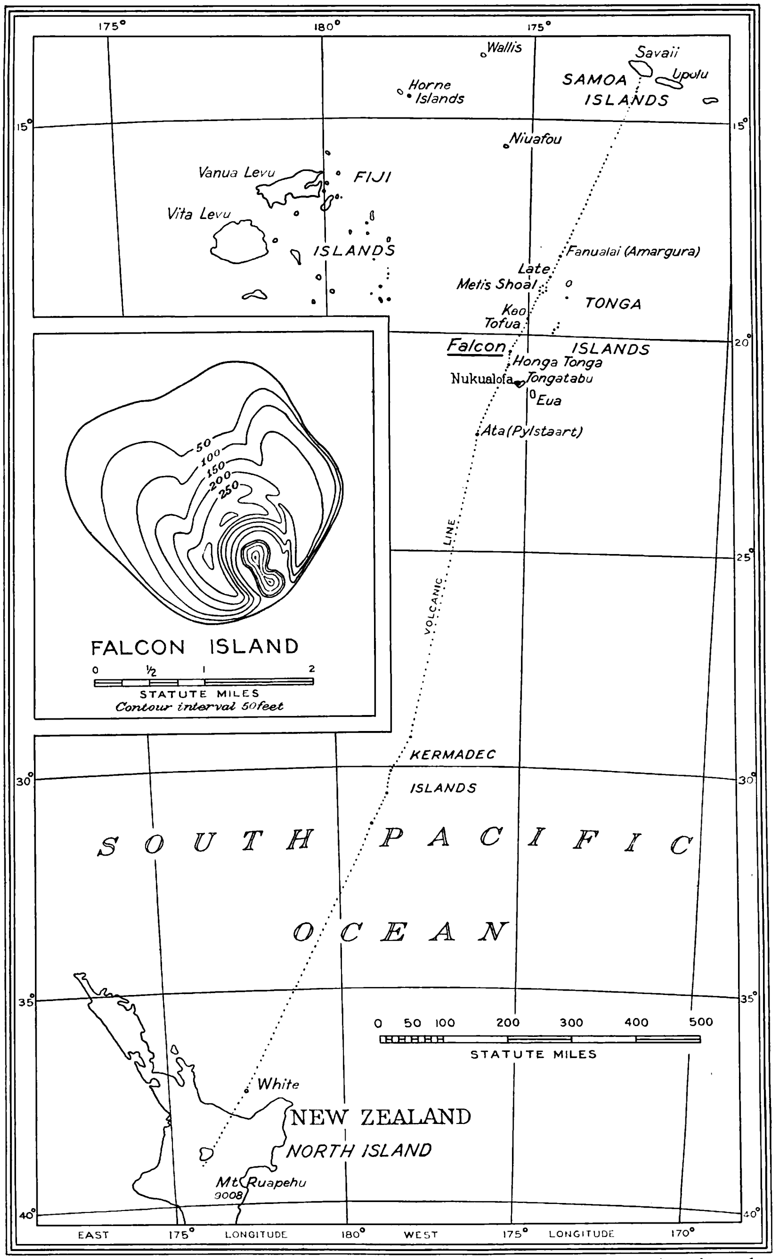

Fig. 1. Map of a portion of the southwest Pacific Ocean showing the location of Falcon and other volcanoes. Insert, contour map of Falcon Island as it appeared in May 1928. From a sketch map by Harry S. Ladd reproduced with the permission of the National Geographic Magazine.

had been removed, the core which remained rising to a height of only 153 feet. During the next six years the cone was reduced to a diameter of less than half a mile and a height of only forty feet. Three years later a shoal one hundred yards in diameter marked the site of Falcon Island. On this shoal the sea broke heavily.

In 1900 a bank was reported to be showing ten feet above water at the northern end of the shoal. This was probably the work of waves and wind which piled the loose material to leeward. In 1913 H. M. S. *Cormoran* visited the spot and reported that the bank had disappeared.

On October fourth, 1927, after nearly half a century of dormancy, the volcano again erupted violently. A few days before the eruption (on September thirtieth) the nearby islands were rocked by a slight earthquake. The eruption ejected a column of steam and dust to a height of several thousand feet. This cloud was clearly visible at Nukualofa, the capital of Tonga, fifty miles to the south. On the third day of the eruption the site was visited by H. M. S. *Laburnum.* At this time the volcano was actively ejecting ashes, cinders and clouds of steam. A cone three hundred feet in height and three miles in circumference had been built above the water.

During the next few months reports of mild activity came at intervals. The volcano was observed in violent eruption by Hoffmeister and Ladd in the early part of May 1928 and was visited by them two weeks later, at which time Ladd spent five hours ashore. The volcano was steaming quietly.[2]

GENERAL FORM AND SIZE.

Falcon is nearly quadrate in outline, the four angles lying at the cardinal points. Viewed from a distance it appears as a low, gently-sloping cone. It is two miles in diameter and rises to a height of three hundred and sixty-five feet. Such, at least, were its approximate dimensions in May 1928. It has been estimated that at this time 12,000,000,000 cubic feet of material lay above sea level.

The contour map in Fig. 1 shows the general shape and configuration of the island. It is composed entirely of pyroclastic material and there is not a single lava flow upon the island. The stuff of which it is made was ejected as agglomerate, a

[2] Hoffmeister, J. Edward, and Ladd, Harry S., Falcon, the Pacific's Newest Island, National Geogr. Mag., **54**, 757-766, 1928; (transcript) Illustrated London News, **174**, No. 4682, 62-64, 1929.

mixture of brownish-gray ash, tuff, scoria, pumice and blocks of solid lava. That part which lies beyond reach of the waves has remained as unsorted and poorly bedded agglomerate but that near sea level has been well sorted by the waves. High cliffs have been cut on the windward (southeast) side and much of the material thus removed has been shifted to leeward where an extensive shoal has been built. The sides of the conical island and the inner walls of the crater are trenched by systems of gullies, the result of heavy tropical rains. Some of these gullies are as much as thirty feet in depth.

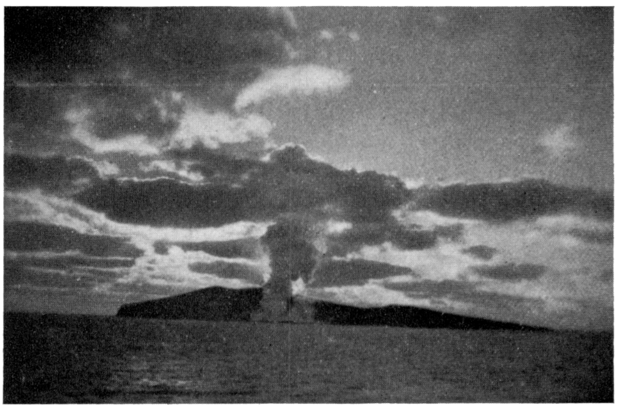

Fig. 2. Falcon Island at sunset. The steam from the crater gives rise to beautiful cloud effects. Photograph by E. Poole.

THE CRATER.

The crater lies to windward on the southeast coast. It is roughly circular in outline and has a diameter from crest to crest of nearly a mile. Almost three-fourths of its rim rises to an elevation of over one hundred and fifty feet above sea level. The highest point lies to leeward, a little north of west. Here the rim reaches an elevation of three hundred and sixty-five feet. To windward the crater wall is breached and storm waves gain free access over a low barrier of reworked scoria. The location of the crater and its asymmetrical form are obviously due chiefly to the prevailing southeast trade winds. During and after eruption these winds transport the finer material to leeward. This process also concentrates volcanic bombs and blocks of solid lava on the windward side. Some of the lava blocks exceed three feet in diameter.

The floor of the crater is elliptical in outline and much of its surface is occupied by a hot salt lake. Locally the flats surrounding the lake are veneered with sulphurous deposits left by hundreds of hissing steam jets. Steam also issues from many points on the crater walls especially on the western side. The inner walls are exceedingly steep, averaging approximately fifty-five degrees. Locally the walls are nearly vertical. There are in reality parts of two craters on Falcon, a younger one with steep walls lying within an older one. The northeastern wall of the inner crater is breached by a steep-walled gulch.

THE CRATER LAKE.

The crater lake is shaped roughly like a figure eight, the constrictions of the figure being due to delta deposits from two important gullies that enter on opposite sides of the crater. The surface of the lake lies at sea level and its waters rise and fall with the tide. The waters are colored a deep milky green near the seaward edge but fade to yellowish white on the opposite side. Clouds of steam arise from the surface of the lake, parts of which boil incessantly.

The water is distinctly acid and carries a considerable amount of free sulphur. A qualitative analysis shows a number of other substances. These are, in order of decreasing amounts: metals; iron, calcium, sodium, magnesium, potassium; non-metals; sulphide, sulphate, sulphite, chloride.

PETROGRAPHY.

A study of several thin sections of samples collected on Falcon shows that the rock is a basic one of basaltic affinities, its textural relations suggesting a diabasic pyroclastic. It is composed in large part of a nearly opaque dark brown glass, the small amount of crystalline matter present being very fine-grained and profoundly stained with oxides of iron.

Rods or lath-shaped crystals of plagioclase feldspar are strikingly embedded in the glass. Many present a zonal structure and when not actually concentrically grown show an undulatory extinction. Extinction angles point to a labradorite of bytownite composition but it seems highly probable that the composition is not uniform but varies. Absolutely untwinned crystals of plagioclase are surprisingly common. These rods are arranged in curiously grouped bunches in some portions of a slide, controlled by blow holes, and in others exhibit a crude parallelism showing distinctly a flow structure.

These portions may be interpreted as inclusions of volcanic matter which represent a previously formed rock, possibly a flow broken up by the recent activity which is responsible for the reappearance of the island.

Stout grains of pale green pyroxene, not far from diopside, can be identified by exploring with the high power. Olivine is probably present but its identification is uncertain. Magnetite, apatite, ilmenite, are more definitely determined. Much of the magnetite is titanium-bearing.

Chemical analyses of volcanic rocks from the part of the Pacific in which Falcon lies are not numerous but they indicate

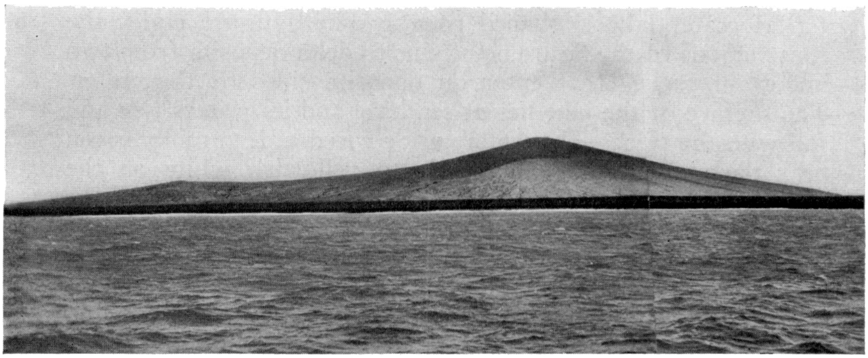

Fig. 3. A view of the leeward coast of Falcon. The black band represents the edge of a flat of reworked scoria which fringes the lee shore. Photograph by J. E. Hoffmeister.

that the rocks in general are basalts. A study of the norms published by Washington[3] of the analyses reproduced in Table I, suggests that nephelite may not be lacking in the Falcon Island cinders. Petrographic study of pyroclastics from Eua,[4] an island in the Tongan Group which lies about sixty miles to the southeast of Falcon, suggests much the same kind of rock.

[3] Washington, H. S., U. S. Geol. Surv., Prof. Paper **99**, 1917.

[4] Lister, J. J., Notes on the Geology of the Tonga Islands, Quart. Jour. of the Geol. Soc. London, **47**, 590-617, 1891.

Harker, Alfred, Notes on a Collection of Rocks from the Tonga Islands, Geol. Mag., **8**, 250-258, 1891. In this article Harker also gives a brief description of some rocks collected on Falcon Island by Lister in 1889 and by Oldham in 1890.

TABLE I.

	Fiji Augite Andesite	Samoa. Basalt	Samoa. Olivine Basalt	Samoa. Nephelite Basalt	Samoa. Basalt
SiO_2	58.92	44.17	45.96	43.76	43.76
Al_2O_3	16.95	18.91	10.94	11.58	11.58
Fe_2O_3	3.33	8.34	5.85	4.39	4.39
FeO	3.69	5.62	6.39	7.57	7.57
MgO	.40	4.87	10.82	12.97	12.97
CaO	6.22	10.64	9.96	9.64	9.64
Na_2O	4.99	1.61	2.40	3.03	3.03
K_2O	3.08	1.50	1.92	1.84	1.84
H_2O+	1.27	.55	.36	.47	.47
H_2O-	1.09		.12		
TiO_2		2.84	5.50	3.41	3.41
P_2O_5		.24	Trace	.45	.45
MnO			.08		
CO_2		.32	None	.38	
NiO			.02		
SO_3				.14	.14
S				.15	.15
Cl		.09			
Total	99.94	99.70	100.32	99.78	99.78

NORM

Quartz	5.76	2.16			
Orthoclase	18.35	8.90	11.12	11.12	11.12
Albite	42.44	13.62	18.34	9.43	8.91
Anorthite	14.18	39.75	13.34	10.01	12.79
Nephelite			1.14	8.52	18.80
Diopside	9.60	8.64	28.08	27.60	25.41
Hypersthene		8.20			
Olivine			9.94	17.04	17.78
Magnetite	4.87	9.74	4.64	6.50	6.50
Ilmenite		5.47	10.49	6.54	6.54
Apatite		.67		1.01	1.01
Wollastonite	2.32				
Hematite		1.60	2.72		

ESTIMATES OF EROSION.

Falcon would be, in some ways, an ideal spot in which to study the relative importance of marine and fluvial erosion. The date of its birth is known and, though but recently formed, the island is composed of unconsolidated material which shows clearly the effects of erosive processes. Its isolated position and the absence of protecting reefs give to the waves their maximum effectiveness. The absence of vegetation on the island coupled with its situation in a part of the tropics where mean annual rainfall is high favor effective fluvial erosion.

The windward half of the island shows strongly cliffed shores. The material is soft and is easily undercut by the waves. From time to time huge sections of the cliffs can be seen sliding bodily into the sea. The highest cliffs are on the eastern side where they are nearly vertical and measure one hundred and twenty-five feet. These cliffs decrease regularly in height to leeward where an extensive flat fringes the shore and extends beneath the sea as a shallow. Above this shallow green water shows for a distance of at least half a mile from shore. The surf everywhere is black with scoria, many of the pieces being fairly well rounded. The immediate shore to leeward is a low bank of scoria fifteen to twenty feet high that

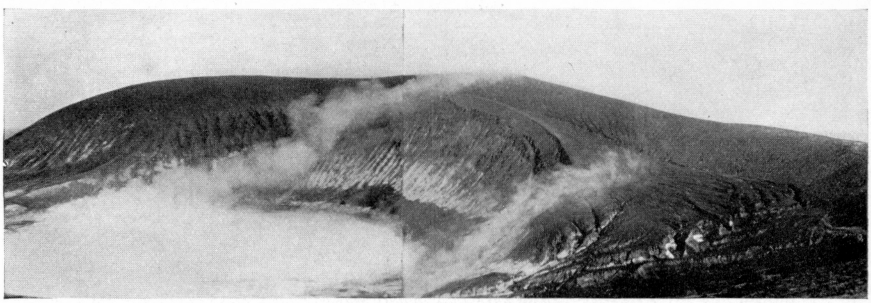

Fig. 4. Falcon's crater as seen from the eastern rim. The white streaks are concentrations of sulphurous deposits. Photograph by H. S. Ladd.

dips seaward at an angle of seventy degrees. To windward the green water marking the shoal extends about one-eighth of a mile from shore. It has been estimated that the sea had removed eighteen mile feet[5] of material from the island at the time of the writers' visit.

All of the steep slopes on Falcon are furrowed with gullies cut by rainwash. On the windward side these gullies terminate along the summits of the sea cliffs as a series of V-shaped notches fifteen to twenty feet deep. The northwest side of the island shows several well developed gully systems though the island slopes are comparatively gentle. These gullies are flat-bottomed and have nearly vertical sides. The inner walls of both craters are a series of contiguous trenches. The large depression that separates the inner crater from the outer one is partly filled with reworked material which dips parallel with

[5] A mile foot is a unit of volume equal to the filling of a square mile to a depth of one foot.

the gradient of the depression. This material is trenched by a gully that measures thirty feet in depth near its mouth. It has been estimated that at the time of the writers' visit the fluvial agencies had removed one-tenth mile feet of material. This estimate and the one for marine erosion previously given are probably not over twice as great as, nor less than half of, their true values. In any case, it seems clear that for very small and very young islands, in a situation similar to that of Falcon, marine attack appears to be of the order of some hundreds of times as rapid as fluvial attack. Doctor C. K. Wentworth, who has estimated the effectiveness of marine versus fluvial erosion in the Hawaiian Islands,[6] has kindly aided the writers in making the above estimates.

EVOLUTION OF SOUTH SEA ISLANDS.

Apparently many islands in the southwest Pacific have been built as Falcon is being built. The explosive eruption, which results in pyroclastic material instead of solid lava flows, seems to have been the dominant type in this area for a long period of time—beginning at least as far back as the Eocene. There is no evidence to indicate that, in the southwest Pacific, pyroclastic action marks merely the waning stages of volcanic activity. Thus, Eua, an island near Falcon, has a core, or base, of volcanic tuff and breccia which contains marine fossils and is overlain by Eocene limestone. The large island of Vitilevu in the nearby Fijian Group is almost entirely covered by fossiliferous tuffs and agglomerates which total several thousand feet in thickness and are Miocene and Pliocene in age. White Island near New Zealand is a more modern representative. It is largely built of material like that composing Falcon. The eruption of the New Zealand volcano, Tarawera, in 1886 was of the Falcon type. Lavas do occur on some of the islands but on those seen by the writers and on many of those described by other workers the lava flows seem subordinate to the fragmental rocks. Such conditions do not exist in the Hawaiian Islands of the north Pacific. Pyroclastic action was relatively important in the building of Oahu, but even on this island, as Wentworth has shown, explosive eruptions played only an insignificant part from the quantitative point of view.[7]

[6] Wentworth, C. K., Estimates of Marine and Fluvial Erosion in Hawaii, Jour. of Geol., 35, 117-133, 1927.
[7] Wentworth, C. K., Pyroclastic Geology of Oahu, Bull. 30, Bernice P. Bishop Museum, p. 3, 1926.

The present Falcon Island may be looked upon as an example of the initial stage of island formation in the South Seas. Eventually volcanic action will cease entirely and the easily eroded mound of ash and scoria will be reduced to a shoal or submarine bank. This bank will be capped by a series of bedded tuffs and similar clastics with some marine fossils included. Rocks of this type are found on many of the elevated islands nearby. This may be called stage two.

Upon the submarine bank thus formed organic deposits will accumulate. This initiates the third stage in the development of the island. If the surface of the bank lies below the depth

Fig. 5. View across the crater lake to windward. Here the crater wall is breached and storm waves gain free access to the lake over a low barrier of reworked scoria. Photograph by J. H. D. Spencer.

limit of reef-building corals, other organisms, such as foraminifera and algae, will be the important limestone builders until the bank reaches a level at which corals can flourish. If the bank is sufficiently stable for a long time an atoll may be produced. The predominance of pyroclastic action in the southwest Pacific seems to be a factor of great importance when considering the origin of the numerous atolls occurring in that area. Islands such as Falcon can be cut down by the waves within a very few years. There results a circular or elliptical bank which may serve admirably as a platform upon which organic deposits can accumulate. If corals and algae become established those growing near the edge of the platform will flourish and atolls may result.

Frequently a fourth stage is recognized. This is introduced by positive movement of the limestone-capped bank. Subsidence would retard the process of island building, while uplift would hasten it. Often the limestones capping the volcanic base are hundreds of feet in thickness and serve effectively in protecting the volcanic material from rapid erosion. Many such banks have been uplifted and frequently the uplift has been periodic as indicated by well developed terraces in the limestone. The island of Eua in Tonga is an excellent example of this fourth stage in island formation. Vatulele, in Fiji, is younger but apparently has had a very similar history.

It seems probable that much of this periodic uplift is due to faulting. In this connection it should be pointed out that Falcon lies along a well marked fault line which stretches for more than one thousand miles from Samoa southward across North Island, New Zealand and Cook Strait into South Island. On this line many volcanoes are located—some active, others dormant or but recently extinct—Savaii, Fanualai, Late, Kao, Tofua, Falcon, Honga Tonga, Ata, Kermadecs, White Island, Tarawera, Tauhara, Tongariro, Ngauruhoe and Ruapehu, and still others in New Zealand. The part of the line which crosses New Zealand marks the great Whakatane fault. The rocks traversed by the fault are "broken, sharply folded, faulted, sheared and uptilted."[8] In South Island the Triassic rocks are faulted against the Miocene.

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[8] Park, James, The Geology of New Zealand, p. 262, 1910.