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Relations between tectonics and magmatology in the northern Danakil Depression (Ethiopia)

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[Plate 19]

Tectonics, volcanism and petrology of the northern Afar (or Danakil) Depression have been investigated during two recent successive expeditions. The tectonics is characterized by numerous NNW trending normal faults.

Two important active volcanic chains, namely Erta'Ale Range and Alayta Range, are disposed in *en échelon* structure. They both display differentiated lavas of subcrustal origin, ranging from abundant basalts to scarce soda-rhyolites with intermediate products, such as dark trachytes as well as oversaturated ones. ^{87}Sr/^{86}Sr isotopic ratios are very low and approximately constant through the whole series. This fact, and other petrological considerations, suggest that this series has not been contaminated by any crustal sialic material.

In addition to these two well-defined volcanic ranges, the Depression is covered by extensive basaltic fields and significant quantities of rhyolites. The variegated petrography of these silicic lavas and ignimbrites, as well as the ^{87}Sr/^{85}Sr ratios, on the contrary strongly suggest that these rocks were formed by interaction between the subcrustal magma and the sialic crust.

It can be tentatively concluded that the sialic crust is missing beneath the northern part of the Danakil Depression only below the two *en échelon* elongated volcanic ranges mentioned above.

INTRODUCTION

Two expeditions to northern Danakil (or Afar) Depression (Ethiopia) took place in December 1967 to February 1968 and November to December 1968. The aim of these expeditions was to study the geology of this area, particularly the tectonic relations of the Danakil Depression with the African rift system and with the Red Sea rift, and to collect petrological and geochemical data on the extensive and nearly unknown volcanism of the Depression.

Some preliminary results on the geology, petrology and geochemistry of the Northern Afar have already been published (Tazieff, Marinelli, Barberi & Varet 1969; Gibson & Tazieff, this volume, p. 331; Cheminee 1969).

In this paper, some relations between the tectonics and magmatology are discussed, on the basis of petrological and isotopic (^{87}Sr/^{86}Sr) data from different volcanic units of the northern Danakil Depression, between latitude 12.5 and 14° N.

GEOLOGICAL OUTLINES OF THE NORTHERN AFAR

In northeastern Ethiopia the plateau escarpment extends parallel to the Red Sea trench, with a NNW trend, up to the extremity of the Zula Gulf, about 60 km south of Massawa. The occurrence of a NNW fault system has been recognized early (Baldacci 1891). The escarpment faulting changes its direction south of the Zula Gulf tending towards NS. The zone of the trend variation corresponds to the maximum of altitude of the crystalline basement with respect to the plateau, which is about 3200 m (Dainelli 1943). The NS alinement continues southwards some hundreds of kilometres as far as the Awash Valley.

Merla & Minucci (1938) recognized the occurrence in the Tigrai plateau of an early system of faults, striking NNW, that is, parallel to the Red Sea; the NS trend to which the eastern escarpment is to be related has been considered to be subsequent. At present a detailed picture of this younger tectonic system is not available. Several NS and NNW faults have been observed during various surveys of this area; they resulted in a gradual steplike lowering of the plateau rocks downwards to the Danakil Depression.† No significant folding has been observed.

Rocks of the ancient crystalline complex which constitutes the eastern escarpment occur also in the Buri peninsula which limits the Zula Gulf to the east and in the Danakil Alps bordering the Red Sea between Thio and Ed. The Buri peninsula seems to be interested by a system of faults mainly NS in trend and therefore parallel to the southern part of the Ethiopian escarpment and also to the opposite coast of Yemen. On the contrary the alinement of the Danakil Alps trends NNW, parallel to the Red Sea rift.

The Danakil Depression extends between the Ethiopian escarpment and the Danakil Alps. Its shape is roughly triangular and very acute towards the north as a result of the discordant directions of the bounding blocks. In the northern part the area is under the sea level (Salt Plain 120 m, Giuletti Lake 70 m) and the depression is filled by recent evaporitic deposits.

An active volcano, Alid, is located nearly in correspondence of the joining zone of the two tectonic trends. This volcano is emplaced on a little horst of crystalline rocks (Dainelli & Marinelli 1912). A recent and still active volcanic range develops along the median axis of the depression (Erta'Ale range) south of the Salt Plain and extends up to the Lake Giulietti. South of the Lake Giulietti several other volcanic units are present; some of them lie in a marginal position within the depression, near the Ethiopian escarpment or the Danakil Alps.

A transversal EW or ENE tectonics is also present either along the escarpment or the Danakil Alps. However, we reach the conviction that this transversal trend is of secondary importance on the basis of field observations and air photograph studies on the lower parts of the escarpment and Danakil Alps. The faults never show parallel patterns nor significant lengths. Therefore, they appear to be produced by gravity readjustments of blocks which were displaced by the primary tectonics, rather than representing another regional fault system. Furthermore, it is to be noted that these ENE transversal faults disappear in the depressed part of the northern Afar.

The northern Danakil Depression is bordered on both sides by a sedimentary series of undefinite Neogene age. It consists of polychrome clastic sediments with gypsum layers and occasionally with intercalations of limestone in the upper part. The series is covered and partly interstratified with extensive masses of weathered basaltic volcanites, most of them deposed in a submarine environment. On the top of the series conglomerate deposits and finally reef limestone of Quaternary age (Faure & Roubet 1968) are present. The Salt Plain, located in the central part of the Depression, is bordered and partly covered by thin clay and sand deposits. The remnants of large submarine flows of basaltic lavas (H. Tazieff, personal communication) outcrop locally; their occurrence is frequently localized at the basis of the subaerial lava flows

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† For example, following the track from Makale to the Salt Plain, at the debouching of the Ain-Ala River, about 100 m above the sea level, layers of Jurassic limestones are present, which commonly occur at about 2500 m in the overhanging Ethiopian plateau.

within the axial volcanic range. Within this volcanic system, a well stratified salt dome has been found, which is uplifted on the western slope of the Gada'Ale volcano. A picrite basalt flow interlayered with salt, is present at the basis of the dome.

The recent volcanic units of the Northern Afar

The northern Danakil Depression is characterized by extensive and very recent volcanism, still active in most places. The several volcanic units outlined from north to south are:

The Erta'Ale volcanic range consists of several volcanic centres and fissural lava fields. Bounded on all sides by recent evaporitic deposits, this volcanic range extends from the Salt Plain to the north to the Giulietti Lake to the south, reaching more than 100 km in length and 20 to 30 km in width, covering an area of about 2500 km^2. The Erta'Ale Volcanic Range is the largest volcanic unit of the Northern Afar and occupies the median part of the Depression. The range is bounded to the south by the lava fields of the next extensive volcanic unit (Alayta).

The Alayta volcanic unit includes the shield volcano, 1400 m high, Alayta *s. str.* located southwest of Giulietti Lake and the extensive fissure-lava fields which surround it in all directions. This unit has an area of about 2200 km^2, in fact identical to that of Erta'Ale Range, but its shape is less enlongated and the lateral widening of the lava flows is limited by the presence of older reliefs. These are represented by the Afdera volcano in the eastern side, and the Boina acidic centre in the south. To the WNW the lava flows of the Alayta system are directly in contact with the escarpment of the Ethiopian plateau.

The volcanological evolution of Alayta is still at the stage of shield volcano by accumulation of fissural lava flows. The trend of the main fissures is NNW and the volcano is affected in its median part by several NNW faults. In the eastern side of the Alayta volcano an important series of NS faults is also present, giving rise to recent and extensive lava flows.

At present time the shield volcano is in a fumarolic stage; the main recent activity appears to consist of the emission of the eastern lava flows. The important eruption in the summer of 1907 reported by Tancredi (1907) and erroneously assigned to Afdera volcano, most probably corresponds to the emissions of fissural lava flows from the eastern side of Alayta.

The main tectonic trend of Alayta system is NNW, perfectly parallel to that of Erta'Ale Range. The two volcanic units are however not coaxial, the Alayta system being located at the west of the prolongation of the Erta'Ale Range axis. The two tectonic axis of the Erta'Ale and Alayta systems are therefore disposed in *en échelon* fashion. In fact, this seems to be one of the most characteristic feature of the Danakil tectonics (Tazieff *et al.* 1969; Gibson & Tazieff, this volume, p. 331).

The Afdera and Borawli-Mat'Ala units. Located south and southeast from Giulietti Lake (figure 1), these units are characterized by the presence of three strato-volcanoes built on basaltic lava flows with associated silicic centres (obsidian flows and subordinate pumices) in the northern part of the Borawli–Mat'Ala unit, and rhyolitic lava-domes south of Mount Afdera. This strato-volcano is mainly constituted by more or less silicic volcanites.

The Borawli–Mat'Ala is the volcanic unit nearest to the Danakil Alps, at the eastern limit of the depression. From a petrographic point of view, this unit is constituted by basaltic rocks, occasionally picritic (as in the northeast of Giulietti Lake) and by their differentiates (basaltic andesites and dark trachytes). In the northern part silicic volcanites, mostly pantelleritic in composition, are abundant, as in the Borawli volcano and in the near obsidian flows.

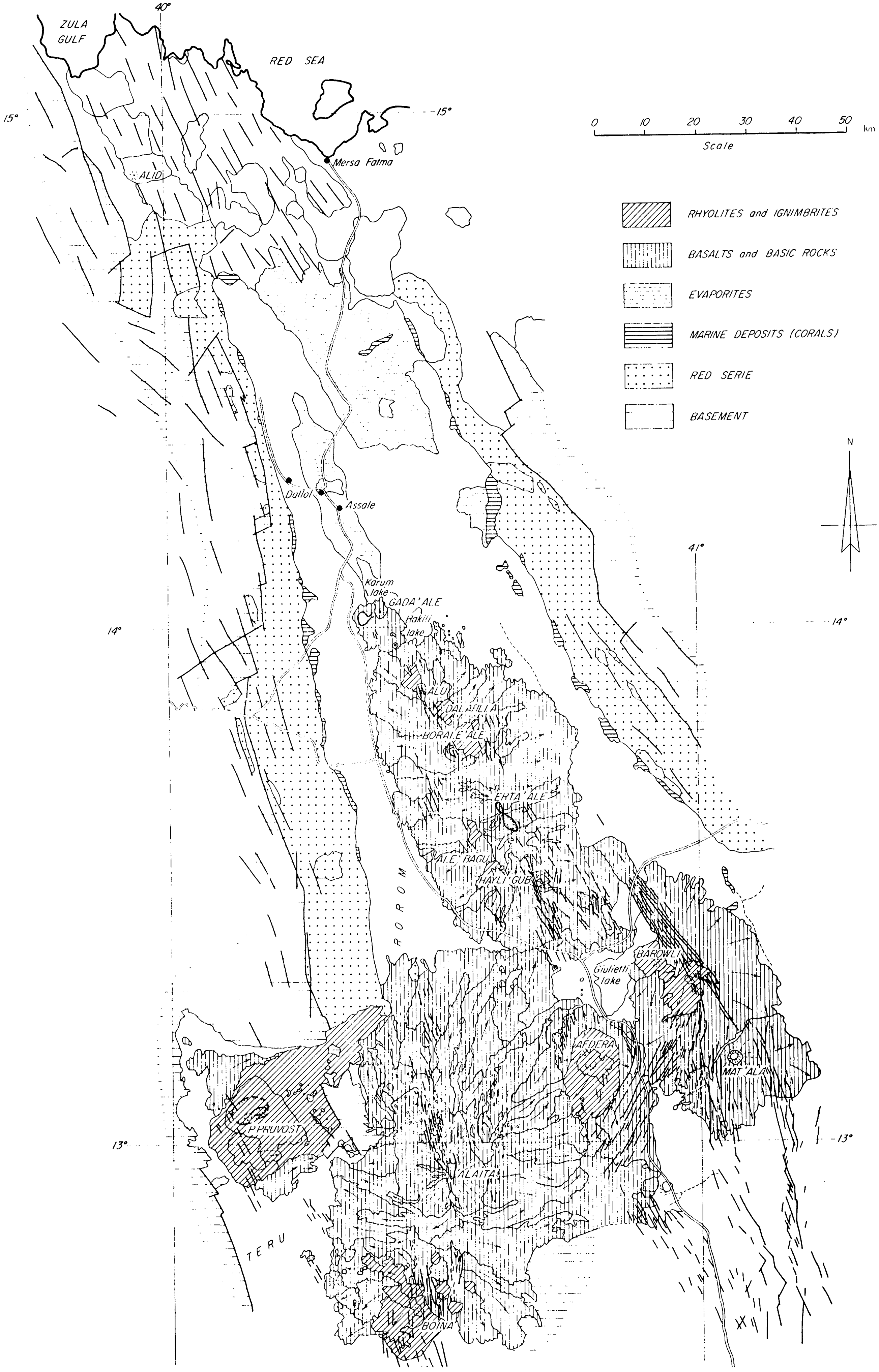

FIGURE 1. Sketchmap of the Northern Danakil Depression with the location of the principal volcanic units.

The northern part of this unit, is still affected by an important fissural tectonics with the usual NNW trend. In the southern part the tectonic is complicated by the presence of a distinct NNE faulting, which affects also the southeastern side of Afdera volcano. At the intersection of these two faulting directions a series of NS faults can be observed; these faults are mostly developed in the Mat'Ala volcano.

The Pierre Pruvost and Boina units. These units are located in the western part of the area under study, very close to the escarpment of the Ethiopian Plateau.

In addition to their geological locations a common characteristic of these two units is the abundance of silicic rocks, such as obsidian flows and domes, ignimbrites and pumices; the basic rocks are represented by comparatively small basaltic lava fields, whose emplacement is mainly anterior to the acidic activity. The Boina unit is affected principally by a NS faulting system. In the Pruvost unit the faulting trend is NNW, typical of the northern Danakil Depression. Another important geological feature is the presence of an outcrop of basement rocks between Pruvost and Alayta; the Pruvost volcanic massif is surrounded on three sides by crystalline basement outcrops.

From this short review of the volcanism in the investigated area, some striking differences between the various volcanic units emerge clearly. At least two different volcanic groups can be distinguished on the basis of their different geological location and of the volume relations and petrographic nature of the volcanic products. The first group is represented by Erta'Ale range and Alayta unit, namely, by the volcanic units located in a central position within the Depression. These units are largely constituted by extensive basaltic lava fields and characterized by a still active tectonics with a series of faults and open fissures clearly NNW in trend. The volcanological evolution within the single units and in the different part of them is more or less advanced; in any case the basic (mostly basaltic) terms largely predominate on the silicic rocks which are limited to the more evoluted volcanic apparatuses. The second group includes all the volcanic units which are mainly located in a marginal position within the Depression, near the crystalline basement of both escarpments. They are characterized by the presence of central volcanoes situated at the intersection of the two different fissure systems and locally showing NNE or NS tectonic trends.

In this group the acidic rocks, mostly represented by pyroclastic products of ignimbritic nature, apparently predominate over the basic fissural lavas. Furthermore, the silicic rocks of the two groups show distinct petrographical and chemical characteristics.

Therefore it seems possible to consider a different origin for the magmatic products of the two groups. It is the aim of this paper to present some petrological and isotopic data in support of this hypothesis. A brief description will be given on the Erta'Ale range and P. Pruvost unit, which can be considered as the more typical representatives of the two volcanic groups and are at the present time the best studied.

ERTA'ALE VOLCANIC RANGE

Tectonics

Figure 2 is a geological sketchmap of the Erta'Ale Range. Proceeding from south to north, a volcanological evolution is clearly visible (Tazieff *et al.* 1969). The southern part is in fact still in the stage of fissural emission of lava flows. Proceeding towards the north, several volcanic phenomena develop, all located on the median axis of the range. They are represented by small

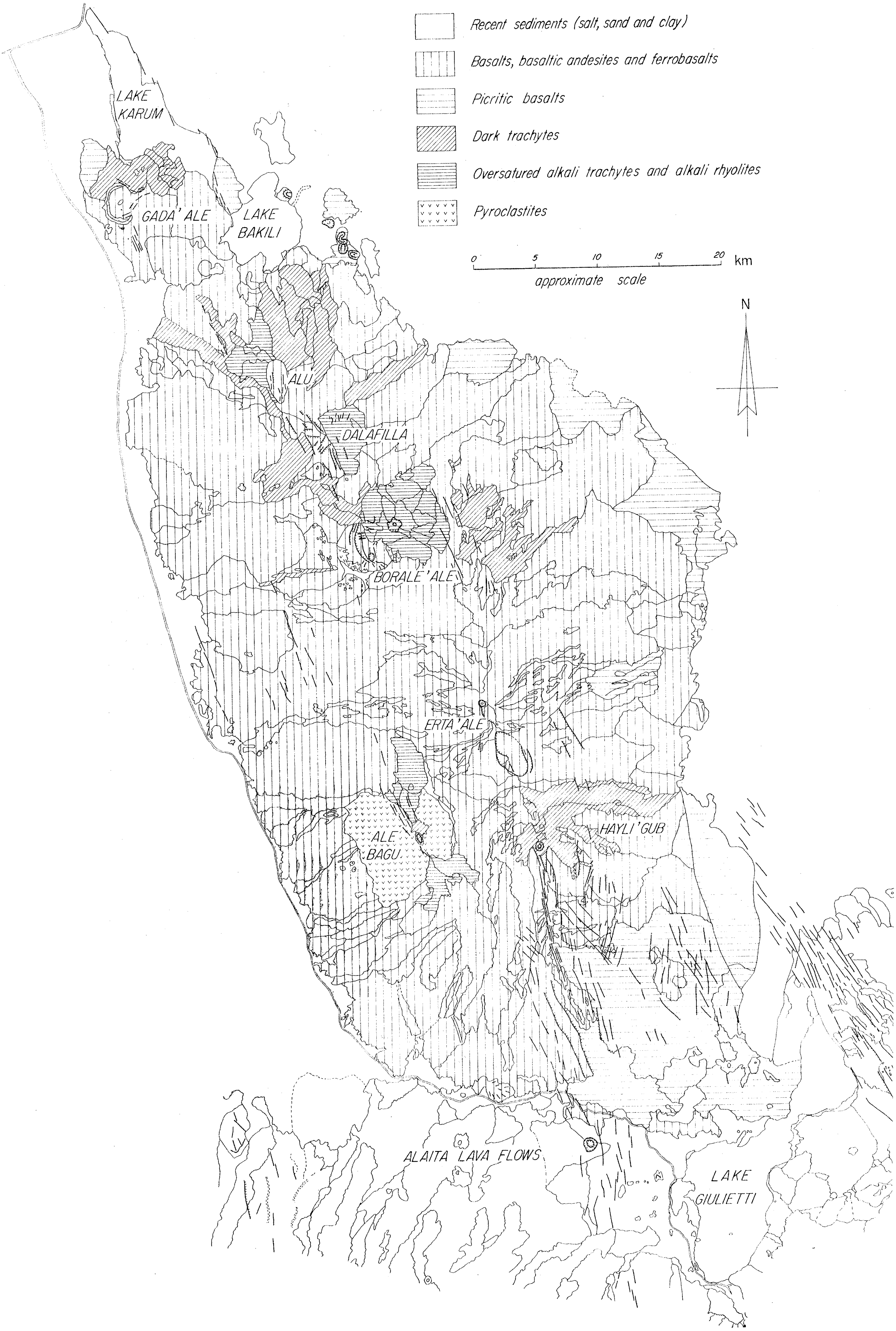

Figure 2. Geological sketchmap of Erta'Ale range.

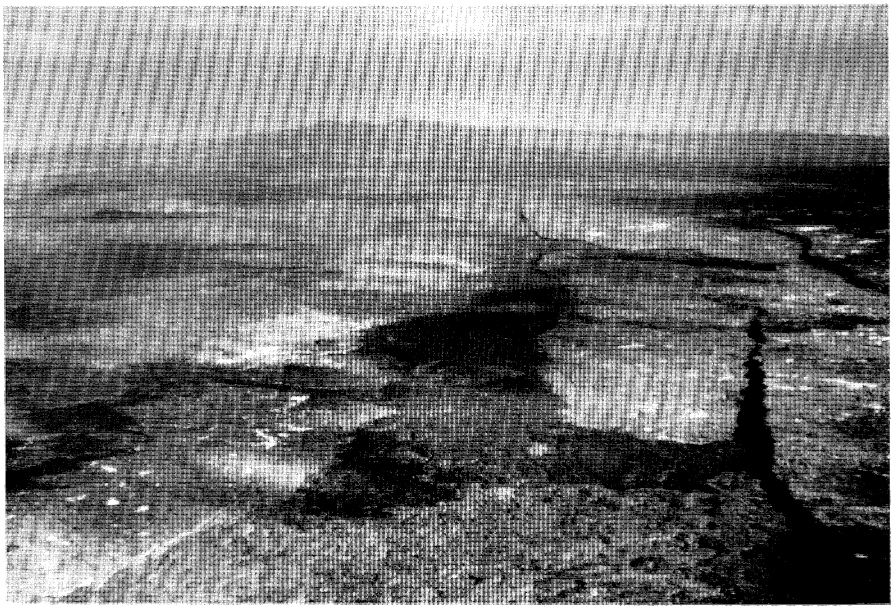

FIGURE 3. NNW faults in the southwest of Erta'Ale range, at east of Lake Giulietti (at right).

FIGURE 4. Southern part of Erta'Ale Range. A small 'graben' occupies the central part of the Range. The more recent flows are located in the median part.

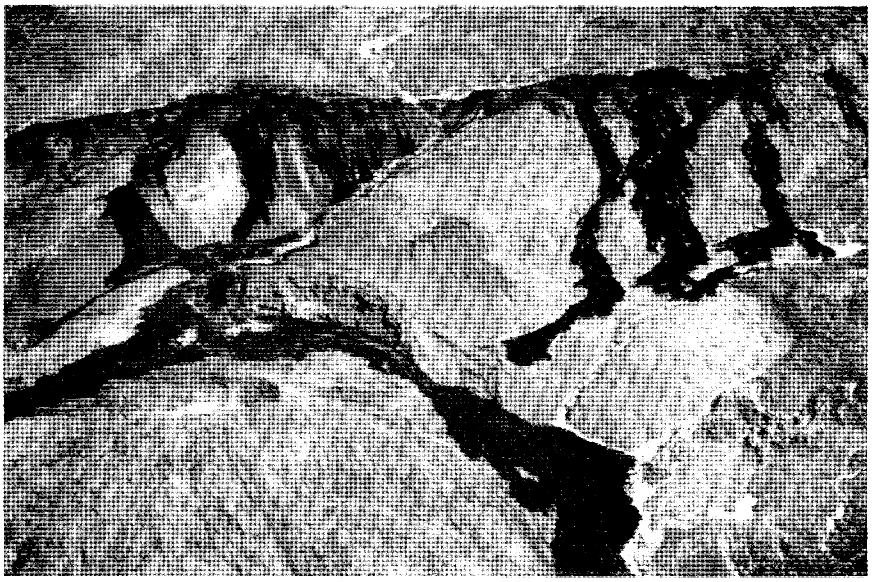

FIGURE 5. NNW fissure, affecting an older strato volcano and generating basalt, in the centre of the range (Borale Ale).

shield volcanoes (Hayli Gub and Erta'Ale) and by more complex central volcanoes as Borale'Ale and Dallaffila. The latter are characterized by abundant and mostly glassy rhyolitic lavas emerging over older basaltic lava fields. Rhyolitic rocks are also represented by obsidian lava flows in the Alu zone and on Ale Bagu, a complex strato-volcano, over 1000 m high with two craters, elongated NNW and located west of the median axis. This is the only volcano in the Erta'Ale range, having a basic pyroclastic cover on the summit around the craters. Acid pyroclastics are extremely scanty; only in the Borale'Ale volcano a thin pumice deposit has been observed.

All the volcanoes are at present in a stage of fumarolic activity, with the exception of Erta'Ale whose main crater was (4 December 1968) partly filled by a molten lava lake with sporadic ejections of lava fountains.

The older volcanic products found in this area are basaltic lava flows probably of submarine origin. The submarine lavas are visible in small outcrops all around the range because they are almost completely covered by the subaerial products.

As already said the range is affected by a main NNW tectonic trend. The importance of this tectonic direction is clearly demonstrated by the following observations: (*a*) the existence in the southern part of several faults and open fissures constantly NNW in direction which give rise to important basaltic lava flows (figure 3, plate 19). The faults and the associated lava flows are progressively younger proceeding from both sides to the centre of the range; the resulting structure is characterized by the presence of a small graben in the median part (figure 4, plate 19) (*b*) the distinct NNW alinement of most central volcanoes along the median axis of the range, which also affects the general form of the craters and small calderas elongated in the same direction; (*c*) the existence of NNW fissures and faults in the northern part which also affect the older central volcanoes giving rise to more recent basic lava or scoriaceous cones (particularly well developed in the Borale'Ale volcano (figure 5, plate 19). This last feature can be considered as a sort of tectonic rejuvenation conducive to the appearance of a new volcanological evolution cycle.

Petrology

The volcanic rocks of the Erta'Ale Range constitute a petrographic suite, ranging from basalts to alkali rhyolites with several intermediate types (Tazieff *et al.* 1969). The total volume of the volcanic products of this range is around 580 km^3. This value is accurate to $\pm 30\%$ because of the imperfect knowledge of the altimetry. The following volume can be estimated with the same approximation for the different volcanic products: basalts (including the less advanced differentiates, basaltic andesites and ferrobasalts), 91.4 %; dark trachytes, 8.1 %; rhyolites, 0.5 %.

The more basic terms in this area are represented by olivine rich basalts showing occasionally a trend toward picritic types. The chemical composition of these basalts is intermediate between alkali basalts and tholeiites. On a pure normative basis most of the analysed samples should be called olivine-tholeiites according to the classification of Yoder & Tilley (1962). Few specimens only contain normative nepheline. On the other hand, the mineralogy is typical of the alkali basalts (absence of orthopyroxene and pigeonite, no reaction relations between olivine and liquid, presence in some specimens of interstitial alkali feldspar, presence of titaniferous augite). Furthermore, if we utilize the Poldervaart classification (1964) for the rocks containing both olivine and hypersthene in the C.I.P.W. norm, most of these rocks belong to the alkalic suite. A simple chemical classification for basaltic rocks has been proposed by several authors (Kuno 1959, 1968; MacDonald & Katsura 1964) by drawing empirical boundary lines in an alkali-silica diagram. In figure 6, in which the boundary lines separating the alkalic, tholeiitic and high-alumina basalt series are redrawn from Kuno (1968), all the analysed rocks from the Erta'Ale range are plotted. The basic rocks are disposed on both sides of the superior boundary line, which according to Kuno (1968) is very near to that drawn by MacDonald & Katsura (1964) to distinguish alkali basalts from tholeiites in the Hawaiian islands. The more silicic terms are enriched in alkalies; they clearly fall in the alkali field.

In the AMF diagram reported in figure 7, the Erta'Ale volcanic series shows a differentiation trend which is different from both the tholeiitic and alkalic suits of Hawaii (MacDonald &

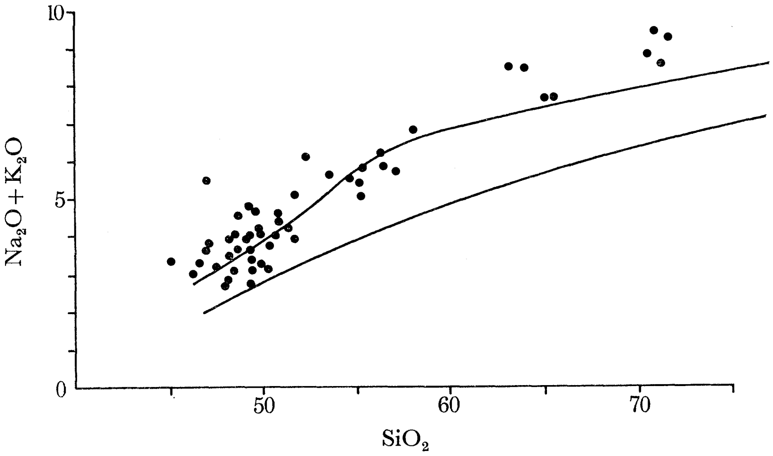

FIGURE 6. Alkali–SiO_2 diagram. The boundary lines are redrawn from Kuno (1968).

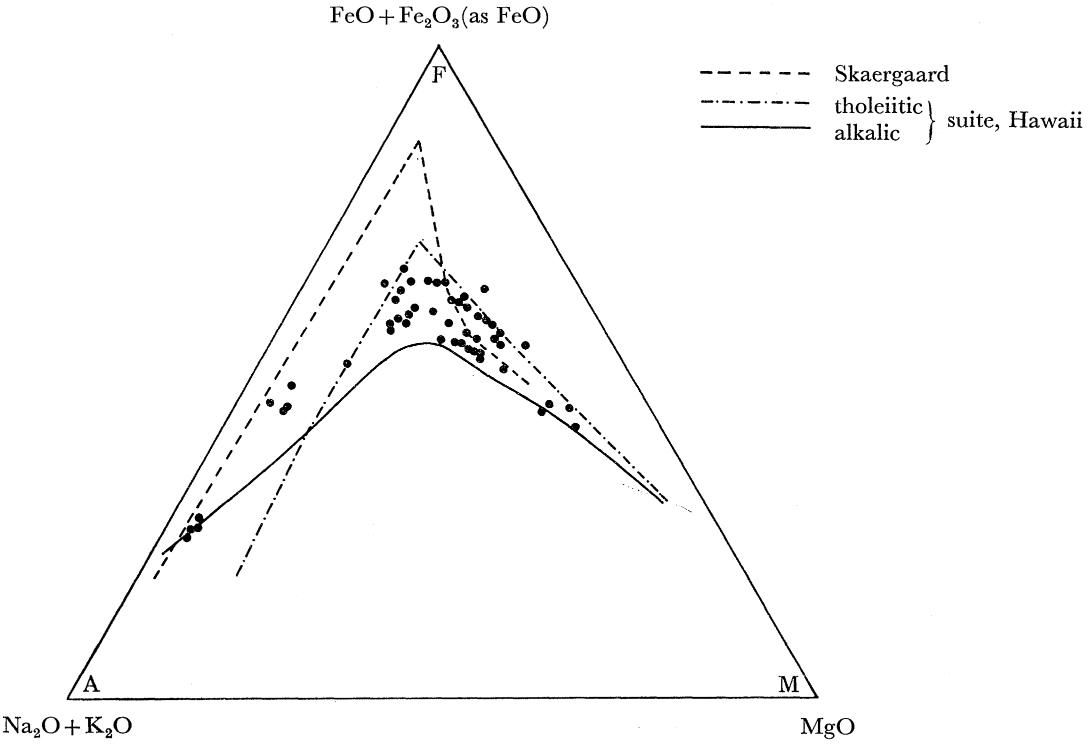

FIGURE 7. A (Na_2O+K_2O)–M(MgO)–F($FeO+Fe_2O_3$ as FeO) diagram for the volcanic rocks of Erta'Ale Range.

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Katsura 1964). This trend is characterized by a distinct iron enrichment in the intermediate terms. These iron rich lavas and other intermediate members of the differentiation series can be called ferrobasalts or basaltic andesites or hawaiites (mugearites for the more advanced terms). The choice of the name is not easy, partly because of the genetic significance which has been attributed by several authors to some of the quoted terms (hawaiites and mugearites as belonging to alkali suite, basaltic andesites and ferrobasalts to the tholeiitic suite). For this reason in a previous note the less common and for many respects unsatisfactory term of andesine-basalts derived from Rittmann's chemical classification (1952) was used (Tazieff *et al.* 1969). Whatever term is employed, the iron rich rocks are mineralogically characterized by the presence of rather sodic plagioclases (from andesine to oligoclase) and the diffusion of iron in the olivine (up to 50 % Fe), clinopyroxenes and opaque oxides, while the orthopyroxene is absent or very rare. These rocks have often a glassy groundmass, dusted by opaque minerals. The main chemical characteristics are a silica content always close to 50 %, low values of Al_2O_3, often less than 10 %, and a very high iron and titanium content ($FeO + Fe_2O_3$ up to 19 %) (table 1).

All the intermediate members between the parental basaltic magma and these strongly iron enriched rocks have been found. Some chemical analyses of all the terms of the petrographic sequence are reported in tables 1 and 2.

Between these iron rich lavas and the final products, oversaturated trachytes and alkali rhyolites, another singular rock-type has been found. This type which was called dark-trachyte in a previous work (Tazieff *et al.* 1969), constitutes very fluid and glassy lavas showing volcanological characteristics very similar to those of basaltic flows (thin and extensive flows of 'aa' and 'pahoehoe' lavas). It gives rise to several and mostly recent flows everywhere in the Erta'Ale range. The almost completely glassy or microcrystalline nature of these rocks permits the recognition of the presence of small andesine-oligoclase crystals bounded by a thin rim of anorthoclase; orthopyroxenes and clinopyroxene are both present and the glassy groundmass is rich of opaque oxides. Chemically they are characterized by a distinct silica enrichment relatively to the basalts. The iron and the titanium content is still relatively high. The feldspar normative composition is distinctly alkaline (anorthite content always less than 10 %). Normatively these rocks are characterized by quartz, sodic alkali feldspar and pyroxene (mostly diopside). For this reason they were called dark-trachyte, this term meaning a rock distinctly alkaline but still rich in mafic components. This is the main feature which distinguish them from the normal trachytic rocks of alkaline suites.

In the authors' opinion, the dark trachytes represent a very important member of the differentiation series; it seems in fact possible to obtain silicic and alkaline final products by simple fractional crystallization of the dark trachytes, mostly by settling of mafic minerals (pyroxenes and iron-titanium oxides). The low viscosity of these lavas, indicated by the practically basaltic characteristics of the flows, removes one of the obstacle stressed by several authors about the possibility of obtaining rhyolitic liquid by fractionation of normally viscous trachytic magma (Mukherjee 1967).

The final products of the volcanic series are represented by oversaturated trachytes and alkali rhyolites. Both types are essentially glassy, and contain scanty and small phenochrysts of anorthoclase feldspar, fayalite and acmitic ferrohedenbergite. The two types are mainly distinguished on the basis of the different silica content (see table 2).

In conclusion, we think that the volcanism along the Erta'Ale range gives rise to a complete

TABLE 1. CHEMICAL ANALYSES AND C.I.P.W. NORMS OF BASALTS, BASALTIC ANDESITES AND FERROBASALTS FROM ERTA'ALE RANGE

		D 12	G 38	CH 50	CH 48	F 98	G 65	CH 28	F 63	CH 22	G 71	E 12 S	F 70	D 8	D 18	F 67	F 77	F 12
SiO_2		44.01	47.93	48.10	49.30	46.20	50.30	49.80	49.87	50.60	48.60	49.67	47.17	48.57	47.03	47.56	46.52	50.71
Al_2O_3		13.75	11.31	13.20	13.40	13.35	14.09	13.50	11.21	13.40	13.10	14.06	10.80	10.33	12.02	9.88	9.47	9.07
Fe_2O_3		5.42	4.39	2.45	2.32	5.42	2.05	2.37	5.58	2.07	2.50	10.53	7.44	4.00	4.15	6.64	8.93	6.32
FeO		5.56	7.87	8.11	8.03	9.03	9.61	9.81	8.23	10.10	10.05	2.11	8.00	10.55	11.45	10.12	10.94	11.24
CaO		11.53	10.60	12.06	12.50	10.75	9.93	10.90	11.44	10.25	10.25	9.85	10.64	10.64	9.07	11.18	10.08	8.62
MgO		10.04	11.85	10.13	9.32	8.81	7.45	6.62	6.25	6.28	5.52	4.76	6.45	5.40	4.96	6.25	6.22	4.83
Na_2O		2.60	2.30	2.45	2.45	2.60	3.06	3.35	2.65	3.35	3.45	3.80	2.95	3.05	4.40	2.55	2.75	3.40
K_2O		0.80	0.41	0.35	0.30	0.43	0.66	0.74	0.60	0.67	1.10	0.85	0.90	0.60	1.10	0.62	0.55	1.17
TiO_2		2.34	1.77	1.45	1.50	1.74	0.99	2.24	2.39	2.10	2.74	2.48	3.20	2.86	3.08	3.30	3.00	3.15
MnO		0.20	0.11	0.17	0.15	0.15	0.07	0.18	0.14	0.19	0.19	0.16	0.19	0.22	0.20	0.17	0.20	0.20
P_2O_5		0.48	0.24	0.24	0.18	0.34	0.17	0.42	0.29	0.36	0.60	0.50	0.36	0.52	0.62	0.43	0.40	0.42
H_2O^+		0.51	1.00	—	—	0.58	0.46	—	0.40	—	—	0.58	0.77	0.37	0.30	0.56	0.50	0.63
H_2O^-		2.57	0.13	1.04	1.00	0.55	0.54	0.82	0.15	0.58	1.50	0.45	0.80	2.06	0.86	0.87	0.28	0.27
total		99.81	99.91	99.75	100.45	99.95	99.38	100.75	99.20	99.95	99.60	99.80	99.67	99.17	99.24	100.13	99.84	100.03
Q		—	—	—	—	—	—	—	4.26	—	—	3.33	1.48	1.74	—	3.11	2.67	4.49
or		4.73	2.42	2.07	1.77	2.54	3.90	4.61	3.54	3.96	6.50	5.02	5.32	3.54	6.50	3.66	3.25	6.91
ab		17.19	19.45	20.72	20.72	21.94	25.88	28.33	22.41	28.33	29.18	32.14	24.95	25.79	29.13	21.57	23.26	28.76
an		23.49	19.33	23.99	24.68	23.49	22.77	19.50	16.92	19.55	17.02	18.80	13.57	12.73	9.81	13.68	11.88	6.04
ne		2.60	—	—	—	—	—	—	—	—	—	—	—	—	4.38	—	—	—
wo	di	12.76	13.23	14.30	15.09	11.53	10.60	13.29	15.83	12.08	12.49	11.19	15.39	15.30	13.00	16.27	14.83	14.19
en		10.33	9.46	9.33	9.67	7.49	5.75	7.24	10.26	6.26	6.43	9.67	11.33	7.94	6.26	10.12	9.16	7.33
fs		0.92	2.60	3.99	4.43	3.25	4.48	5.58	4.50	5.49	5.74	—	2.59	6.94	6.53	5.18	4.81	6.48
en	hy	—	10.26	2.67	5.41	4.09	6.50	1.67	5.30	5.90	0.79	2.18	4.73	5.50	—	5.44	6.33	4.69
fs		—	2.82	1.14	2.48	1.77	5.06	1.29	2.32	5.18	0.70	—	1.08	4.81	—	2.79	3.32	4.15
fo		10.28	6.86	9.26	5.69	7.25	4.41	5.30	—	2.43	4.58	—	—	—	4.26	—	—	—
fa		1.01	2.08	4.37	2.87	3.47	3.79	4.50	—	2.35	4.51	—	—	—	4.90	—	—	—
mt		7.86	6.37	3.55	3.36	7.86	2.97	3.44	8.09	3.00	3.52	0.14	10.69	5.80	6.02	9.63	12.95	9.09
hm		—	—	—	—	—	—	—	—	—	—	10.44	—	—	—	—	—	—
il		4.44	3.36	2.75	2.85	3.30	1.88	4.25	4.54	3.99	5.20	4.71	6.08	5.43	5.85	6.27	5.70	5.98
ap		1.14	0.57	0.57	0.43	0.81	0.43	1.00	0.69	0.85	1.42	1.19	0.85	1.23	1.47	1.02	0.95	1.00

D 12 pictritic basalt NE of Alu (subaerial lava covering a small jaloclastite volcano); G 38 picritic basalt, salt-dome; CH 50 picritic basalt, southern fissural lava flow; CH 48 and G 65 basalts, southern fissures and Erta'Ale; F 98 basaltic submarine flow covered by Alayta lava flows; CH 28, CH 22, F 63, G 71 and E 12 S basaltic andesites, Alu, Ale Bagu and southern fissures; F 70 and D 8 basaltic andesites transitional to dark trachytes, Ale Bagu and northern lava fields; D 18 block, Erta'Ale volcano. F 67 and F 12 ferrobasalts, Ale Bagu and Erta'Ale; F 77 ferrobasalts, submarine flow covered by Alayta lava fields; G 38, CH 48, CH 28, F 63, CH 22, F 70, G 71 and F 12 already published (Tazieff *et al.* 1969).

differentiation series with several rock types. It is important to observe that the volume relations among the different members of the series clearly indicate a continuous decrease in the quantity of the products with the proceeding of the differentiation. In figure 8, the main chemical variation in the volcanic series are shown. The mass percentage of the principal oxides are related with the Kuno solidification index (s.i.) ($MgO \times 100/MgO + FeO + Fe_2O_3 + Na_2O + K_2O$).

TABLE 2. CHEMICAL ANALYSES AND C.I.P.W. NORMS OF DARK TRACHYTES AND RHYOLITES FROM ERTA'ALE RANGE

	D 73	CH 64	F 46	F 55	CH 57	TD 7	D 87	F 59	F 53	F 56	CH 20
SiO_2	58.06	53.50	55.28	56.30	63.10	64.00	65.46	65.15	71.22	70.55	71.60
Al_2O_3	14.26	11.70	9.52	10.65	12.40	12.60	13.45	12.02	13.11	12.60	11.50
Fe_2O_3	2.39	2.55	6.78	5.05	1.30	1.52	1.91	3.51	1.13	0.92	1.03
FeO	7.25	12.13	8.59	8.76	6.79	6.41	5.13	4.66	2.52	2.63	2.45
CaO	5.04	6.72	6.44	5.60	3.58	3.54	3.02	3.13	1.61	1.65	1.44
MgO	2.21	3.07	2.42	3.43	1.24	1.22	0.72	0.88	0.45	0.53	0.42
Na_2O	4.50	3.90	4.15	4.95	5.00	4.90	4.90	5.60	5.77	6.18	6.10
K_2O	2.30	1.70	1.60	1.25	3.50	3.55	2.80	2.05	2.75	2.65	3.15
TiO_2	1.50	2.74	2.10	2.21	1.07	1.09	0.84	0.87	0.47	0.59	0.42
MnO	0.14	0.22	0.23	0.22	0.20	0.23	0.20	0.18	0.14	0.14	0.16
P_2O_5	0.62	1.21	0.82	0.70	0.37	0.40	0.18	0.25	0.10	0.15	0.08
H_2O^-	0.40	0.38	0.76	0.63	—	—	0.54	0.34	0.09	—	—
H_2O^+	0.57	0.06	0.67	0.15	0.61	0.93	0.32	0.97	0.58	1.29	1.01
total	99.24	99.88	99.36	99.90	99.16	100.39	99.47	99.61	99.94	99.88	99.36
Q	8.56	4.92	11.80	7.96	10.59	12.30	17.71	18.02	23.08	20.87	24.75
or	13.59	10.04	9.45	7.38	20.86	20.97	16.54	12.11	16.25	15.66	18.61
ab	38.06	32.98	35.18	41.86	42.29	41.44	41.44	47.36	48.80	50.05	41.61
an	11.92	9.40	2.58	3.16	0.97	1.91	6.44	1.62	1.76	—	—
ac	—	—	—	—	—	—	—	—	—	1.95	2.89
wo	3.77	6.69	10.02	8.37	6.00	5.44	3.07	5.13	2.33	3.01	2.76
en } di	1.44	2.23	4.53	4.07	1.49	1.43	0.68	1.72	0.64	0.80	0.60
fs	2.39	4.68	5.44	4.16	4.85	4.31	2.59	3.57	1.81	2.37	2.35
en } hy	4.06	5.42	1.47	4.47	1.59	1.61	1.11	0.48	0.48	0.52	0.45
fs	6.73	11.37	1.77	4.58	5.18	4.87	4.23	0.99	1.37	1.55	1.75
mt	3.46	3.70	9.70	7.21	1.83	2.15	2.77	5.09	1.64	0.36	—
il	2.85	5.20	3.99	4.20	2.03	2.07	1.59	1.65	0.89	1.12	0.80
ns	—	—	—	—	—	—	—	—	—	—	1.56
ap	1.47	2.87	1.94	1.66	0.88	0.95	0.43	0.59	0.24	0.36	0.19

D 73 and CH 64 dark trachytes Hayli'Gub; F 46 and F 55 dark trachytes Gadda'Ale and Alu; CH 57 and TD 7 oversaturated alkali-trachytes Ale Bagu; D 87, F 59 and F 53 alkali rhyolites Ale Bagu, Dallaffila and Alu; F 56 and CH 20 hyperalcaline pantellerites Alu-Dallaffila; F 46, F 55, CH 57, TD 7, F 53 and CH 20 already published (Tazieff *et al.* 1969).

Few comments are needed. The silica content, unchanged through the initial trend of differentiation, begin to increase only with the dark trachytes, at an s.i. lower than 20.† The alkalies continuously increase, but the K_2O enrichment becomes sensible only in the final stage of differentiation. Na_2O is always largely dominant over K_2O. Iron, titanium and phosphorus show similar trends, characterized by the presence of a maximum which is located around an s.i. of 20 for iron and titanium, and slightly retarded for P_2O_5 (s.i. = 13). The iron variation trend is very similar to that observed in the Skaergaard sequence as reported by Kuno (1968).

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† This observation confirms once more that it is often necessary to employ some parameter different from the silica percentage in the variation diagrams.

Strontium isotopic analyses

In table 3 the data of $^{87}Sr/^{86}Sr$ ratios and Sr, Rb, K contents obtained on Erta'Ale range samples are reported. All the principal terms of the volcanic series have been analysed.

The Rb and Sr analyses were performed using standard procedures of chemical separation and isotope dilution techniques. Sr isotopic composition were carried out on unspiked samples, by means of an Atlas CH 4 mass spectrometer, equipped with a ion multiplier. A sea-water

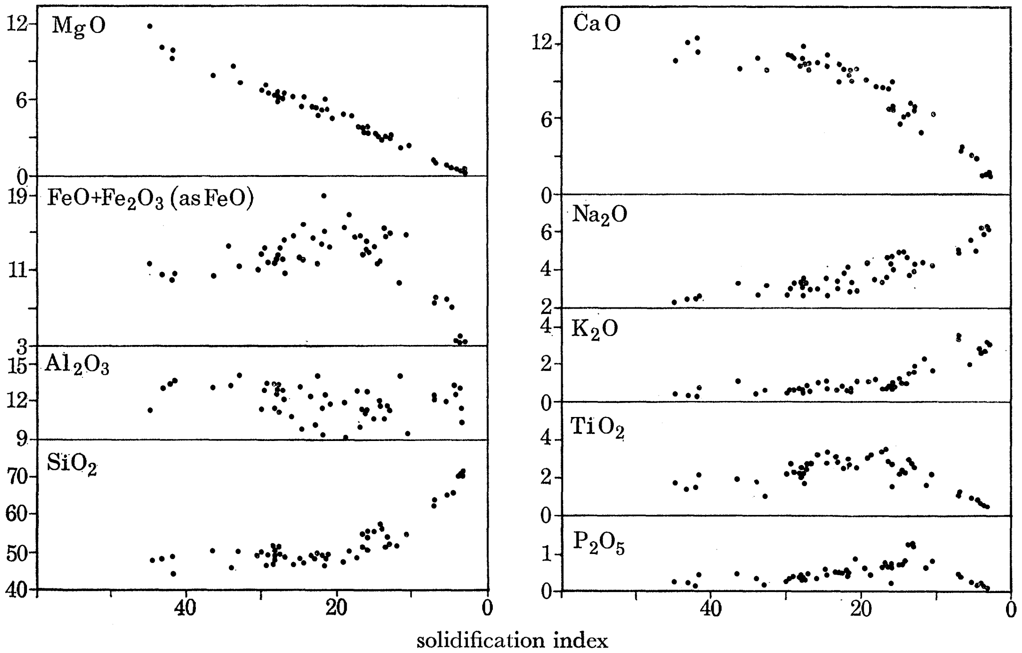

FIGURE 8. Solidification index (MgO × 100/MgO + FeO + Fe_2O_3 (as FeO) + Na_2O + K_2O) variation diagram.

TABLE 3

samples	Rb (parts/10^6)	Sr (parts/10^6)	K/Rb	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$†
	Erta'Ale range				
CH 50, picritic basalt	5.2	241	557	0.06	0.7022
G 65, basalt	13.6	347	404	0.11	0.7048
F 49, basalt	10.7	293	411	0.10	0.7039
F 12, ferrobasalt	25.0	317	388	0.23	0.7032
F 46, dark trachyte	40.0	235	332	0.50	0.7029
F 55, dark trachyte	29.5	265	349	0.32	0.7024
TD 7, oversaturated alkali-trach.	87.0	242	338	1.04	0.7013
CH 57, oversaturated alkali-trach.	83.0	227	349	1.05	0.7036
F 53, alkali rhyolite	70.5	95	323	2.15	0.7032
F 47, alkali rhyolite	57.0	149	322	1.10	0.7039
CH 20, alkali rhyolite	77.0	96	339	2.30	0.7044
	Alayta unit				
F 143, dark trachyte	33.4	381	371	0.25	0.7028
F 147, dark trachyte	36.0	404	344	0.26	0.7053
F 98, basalt	7.4	349	472	0.06	0.7042
G 70, basalt	10.7	385	435	0.08	0.7029
F 77, ferrobasalt	10.2	370	449	0.08	0.7050

† Normalized to $^{86}Sr/^{88}Sr = 0.1194$; $^{87}Sr/^{86}Sr$ ratio error is ± 0.001.

strontium standard has been used to monitor the isotope ratios. The $^{87}Sr/^{86}Sr$ ratios were normalized to $^{86}Sr/^{88}Sr = 0.1194$.

In table 3 the data obtained on samples of the Alayta unit are also reported. The petrology of the Alayta volcanites is very similar to that of the Erta'Ale range, but the magmatic evolution is less advanced, since the petrographic series ranges from basalts to dark trachytes (see table 4). The most advanced terms, as oversaturated trachytes and rhyolites, are missing.

All the values of the $^{87}Sr/^{86}Sr$ ratios are closely grouped, ranging between 0.702 and 0.705. No systematic differences have been observed between ratio values in terms of the petrographic series. This is particularly evident in figure 9 where the Sr isotopic ratios have been related to

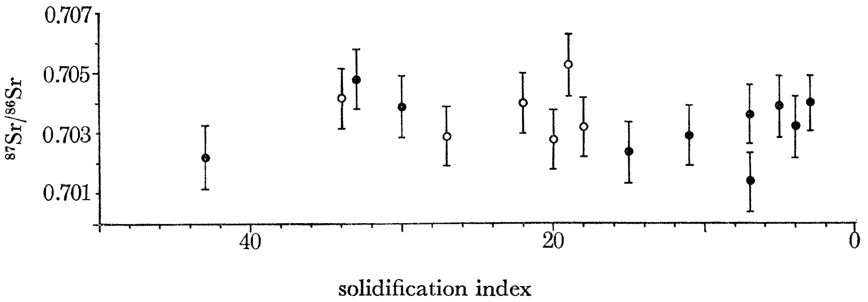

FIGURE 9. $^{87}Sr/^{86}Sr$ ratios for (•) Erta'Ale and (○) Alayta volcanites related to solidification index.

TABLE 4. BASALTS AND DARK TRACHYTES FROM ALAYTA

	D 194	D 195	D 200	G 70	F 143	F 147
SiO_2	46.18	48.40	47.95	46.95	52.75	53.68
Al_2O_3	10.70	11.82	13.08	13.68	14.22	13.56
Fe_2O_3	4.00	5.26	4.14	3.30	2.03	1.07
FeO	12.42	10.48	8.36	10.48	8.86	9.56
CaO	10.30	8.62	10.97	10.62	7.23	7.39
MgO	5.64	5.16	7.90	6.32	3.74	3.72
Na_2O	2.80	3.30	2.60	2.74	3.95	3.88
K_2O	0.70	0.90	0.45	0.64	1.50	1.50
TiO_2	4.30	3.96	2.54	3.45	2.60	2.72
MnO	0.26	0.19	0.15	0.22	0.25	0.26
P_2O_5	0.40	0.68	0.18	0.31	1.10	1.12
H_2O^-	0.65	0.40	0.58	—	0.24	—
H_2O^+	1.21	0.64	0.66	1.21	1.12	1.06
total	99.56	99.81	99.56	99.92	99.69	99.52
Q	—	2.65	—	—	3.79	4.47
or	4.13	5.32	2.66	3.78	8.86	8.86
ab	23.68	27.91	21.99	23.17	33.41	32.82
an	14.56	14.79	22.69	23.14	16.64	15.16
wo } di	14.16	9.82	12.75	11.49	5.02	5.92
en } di	7.21	5.60	8.41	6.43	2.31	2.51
fs } di	6.61	3.80	3.43	4.59	2.67	3.43
en } hy	5.54	7.24	9.47	5.21	7.00	6.75
fs } hy	5.09	4.91	3.86	3.72	8.09	9.23
fo	0.90	—	1.25	2.87	—	—
fa	0.91	—	0.56	2.25	—	—
mt	5.80	7.63	6.00	4.78	2.94	1.55
il	8.17	7.52	4.82	6.55	4.94	5.17
ap	0.95	1.61	0.43	0.73	2.61	2.66

D 194 and D 195 basaltic andesites from the shield volcano: D 200 and G 70 basalts, fissural lava flows; F 143 and F 147 dark trachytes.

the solidification index of the analysed samples. It is to be noted that the observed range is typical for rocks of subcrustal origin such as oceanic basalts and volcanites of Western Pacific islands arcs. These constantly low values of the Sr isotopic ratios rules out any significant process of contamination with crustal rocks, which are characterized by remarkably higher values of the $^{87}Sr/^{86}Sr$ ratios (Hedge 1966; Pushkar 1968; Armstrong 1968).

PIERRE PRUVOST MASSIF

Figure 10 is a sketch map of Pierre Pruvost† massif. Several volcanic phases can be distinguished in this area. In the order of chronological succession they are:

(*a*) Outpouring of fissural basaltic lava flows.

(*b*) Emplacement of ignimbritic units particularly south and northeast of the strato-volcano. Three ignimbritic sheets have been observed. The first two (each 4 m thick) are separated by a thin layer of pumice and covered by a thicker flow of pumice (30 m). Before the emplacement of the third ignimbritic unit (10 m thick), basaltic activity resumed with associated building of small scoriaceous cones.

(*c*) Building of the big strato-volcano Pierre Pruvost *s.str.*, constituted by several obsidian flows, pumice and pyroclastic layers, porphyritic trachyte flows and domes, particularly well visible in the walls of the caldera located in the summit of the volcano. The more recent volcanic product in the caldera is represented by an ignimbritic layer. The strato-volcano is cut by recent NNW faults, along some of which basaltic scoriaceous cones are present.

(*d*) Building of rhyolitic lava domes and outpouring of fissural obsidian flows along two distinct NNW fissures south of the strato-volcano. In this acid centre some steam-fumaroles have been observed.

All the recent visible tectonics are clearly NNW in trend. Other possible trends, acting in the formation of the large strato-volcano, are however not visible. The authors can only call attention to the transversal elongation of the caldera.

Petrology

The Pruvost acid volcanites show varying mineralogical compositions and degree of crystallization. Some of the very recent lavas, outflows from the base of the cone, are nearly crystal free; on the other hand, the ignimbrite occurring in the caldera internal wall, is very rich in phenocrysts, although a lot of them may be considered xenocrysts. The sanidine is the most diffused mineral occurring either as well shaped and limpid crystals or as cloudy microperthitic or micropegmatitic grains irergularly shaped. Anorthoclase feldspar is uncommon; sometimes it seems a substitution product of older plagioclase crystals rather than a mineral directly crystallized from the magma. Oligoclase-andesine plagioclase have been recognized in some samples. They are strongly corroded and very frequently bordered by sanidine rims. Occasionally a transformation in anorthoclase has been observed. Detailed studies on the feldspars and residual liquid composition are needed in order to reconstruct the crystallization history of these rocks. Strongly corroded crystal fragments of quartz are diffuse only in rocks very rich in crystals. The commonest mafic minerals are represented by a clinopyroxene never strongly alkaline and by fayalite. Alkaline amphiboles, cossyrite and biotite occur in a few of the samples. An ignimbrite outcropping as the southeastern basis of the Pruvost volcano contains aegirine-augite, katophorite, biotite and cossyrite. This could represent an unstable mineralogical assemblage.

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† So called in honour of the late French geologist Pierre Pruvost (Tazieff *et al.* 1969).

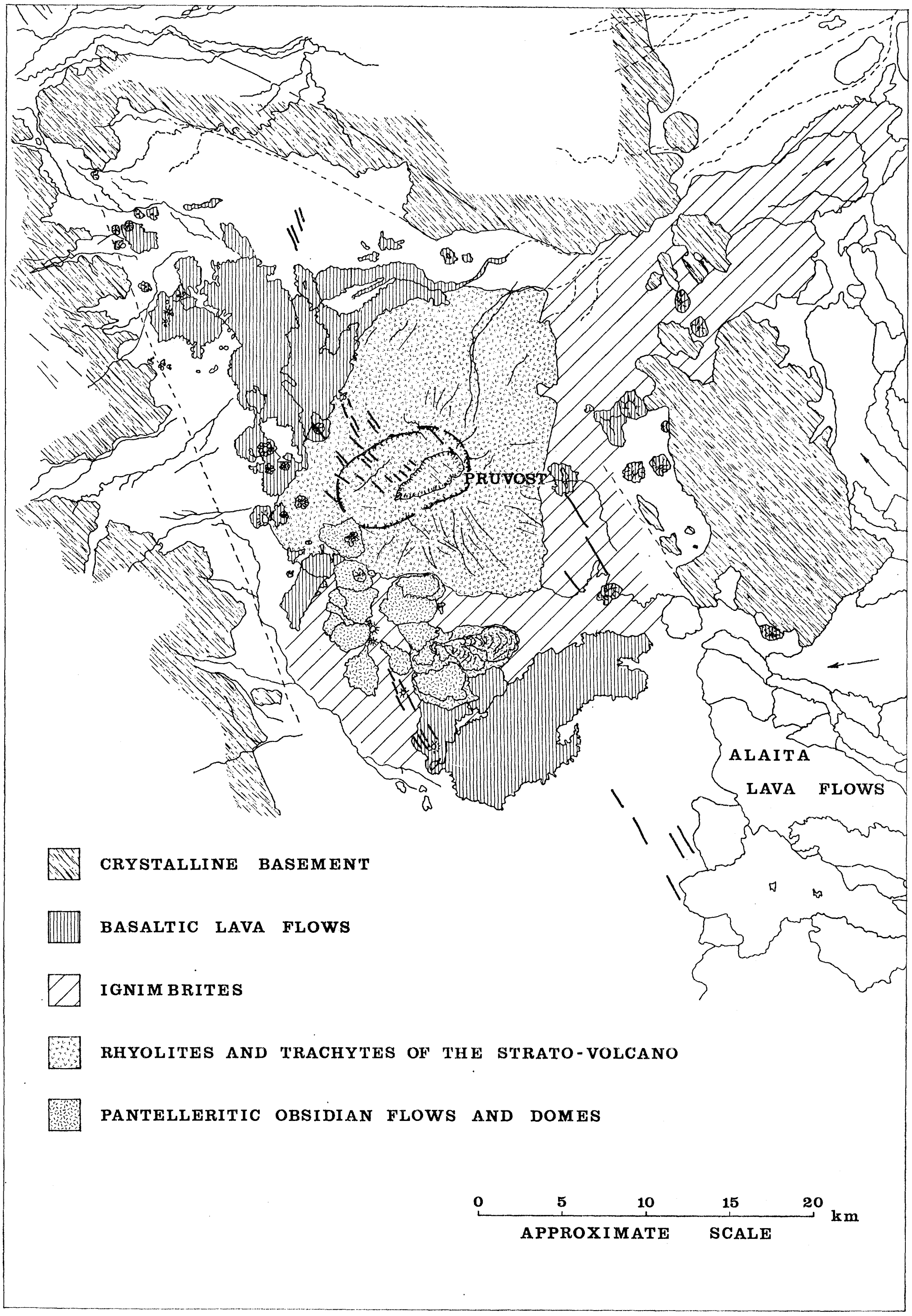

FIGURE 10. Geological sketchmap of P. Pruvost massif.

Chemical analyses of some Pruvost volcanites are reported in table 5. The chemical composition of acidic volcanites ranges from alkali-trachytes to hyperalkaline trachytes and pantellerites, often containing normative sodium metasilicate.

The more striking chemical difference between these rocks and the trachytic and rhyolitic types of the Erta'Ale range consists in a marked decrease of the Na_2O/K_2O ratio. This clearly results from the Na_2O–K_2O–CaO diagram of figure 11 where the Pruvost alkaline rocks are clearly displaced towards the K_2O corner, relatively to the Erta'Ale volcanic series. The more potassic character of the Pruvost volcanites is also evident from the diffusion of sanidine crystals which are completely lacking in the Erta'Ale alkaline rocks.

Other significant differences between the two volcanic zones are the lack of intermediate products in the Pruvost unit, the more varied mineralogy of the Pruvost rocks, some of which probably contains also xenocrysts, and finally the almost reversed volume relations between the acid and basic products of the two zones.

TABLE 5. CHEMICAL ANALYSIS AND C.I.P.W. NORMS OF VOLCANIC ROCKS FROM PRUVOST AND BOINA MASSIFS

	G 35	G 31	G 28	D 174	D 175	D 176	D 168	D 169	CH 9	CH 15	D 217	D 224	D 222
SiO_2	49.38	64.86	63.70	63.51	65.91	66.57	67.95	68.88	67.00	71.20	65.02	68.40	71.03
Al_2O_3	15.31	10.65	13.80	16.63	15.18	14.26	13.65	14.37	12.50	11.60	14.88	12.53	8.86
Fe_2O_3	4.33	2.51	5.06	3.67	1.91	1.43	0.79	1.59	3.63	1.58	1.75	2.55	2.87
FeO	6.16	3.10	0.44	1.22	2.97	3.16	2.97	2.04	2.07	2.33	3.48	2.94	4.23
CaO	11.16	2.25	1.81	0.89	2.07	2.12	1.40	1.45	1.25	0.43	1.34	1.00	0.61
MgO	7.86	0.32	0.61	0.16	0.64	0.80	0.32	0.40	0.06	0.04	0.24	0.16	0.32
Na_2O	2.70	5.50	6.00	6.10	4.90	4.75	4.50	4.75	6.40	6.20	5.90	5.90	5.70
K_2O	0.62	4.60	5.25	4.60	4.45	4.55	5.00	5.00	5.55	5.15	4.30	4.50	4.40
TiO_2	1.25	0.35	0.69	0.16	0.58	0.58	0.39	0.32	0.36	0.25	0.36	0.22	0.36
MnO	0.10	0.18	0.22	0.06	0.02	0.07	0.04	0.06	0.27	0.14	0.13	0.16	0.15
P_2O_5	0.26	0.03	0.22	0.02	0.12	0.11	0.07	0.07	0.02	—	0.04	0.04	0.04
H_2O^-	0.40	1.16	—	0.58	0.63	0.73	0.20	0.50	—	—	0.62	0.31	0.22
H_2O^+	0.06	3.62	1.94	2.25	0.31	0.18	2.66	0.37	0.57	0.65	1.89	0.89	0.86
total	99.59	99.13	99.74	99.85	99.69	99.31	99.94	99.80	99.68	99.57	99.95	99.60	99.65
Q	—	17.07	8.26	8.36	14.69	15.62	18.36	18.49	13.32	23.60	10.13	16.34	28.90
or	3.66	27.18	31.02	27.18	26.29	26.88	29.54	29.54	32.79	30.43	25.40	26.59	26.00
ab	22.84	29.17	41.75	51.59	41.44	40.17	38.06	40.17	33.40	30.99	49.90	39.39	21.08
an	27.83	—	—	4.28	6.29	4.16	2.29	3.13	—	—	1.43	—	—
c	—	—	—	0.05	—	—	—	—	—	—	—	—	—
ac	—	7.26	7.92	—	—	—	—	—	10.41	4.45	—	7.38	8.30
wo	10.78	4.58	3.07	—	1.33	2.35	1.75	1.50	2.53	0.89	2.07	1.96	1.15
en di	7.59	0.64	1.52	—	0.48	0.83	0.30	0.51	0.07	0.02	0.26	0.15	0.12
fs	2.27	4.36	—	—	0.89	1.58	1.60	1.04	2.78	0.98	2.01	2.03	1.15
en hy	10.19	0.16	—	0.40	1.12	1.16	0.50	0.48	0.02	0.08	0.34	0.25	0.67
fs	3.05	1.09	—	—	2.07	2.21	2.63	0.98	0.93	3.15	2.58	3.30	6.30
fo	1.25	—	—	—	—	—	—	—	—	—	—	—	—
fa	0.41	—	—	—	—	—	—	—	—	—	—	—	—
mt	6.28	—	0.14	3.66	2.77	2.07	1.14	2.30	—	—	2.54	—	—
hm	—	—	2.23	1.14	—	—	—	—	—	—	—	—	—
il	2.37	0.66	1.31	0.30	1.10	1.10	0.74	0.61	0.68	0.47	0.68	0.42	0.68
ns	—	2.12	—	—	—	—	—	—	2.07	3.81	—	0.50	4.12
ap	0.62	0.07	0.52	0.05	0.28	0.26	0.17	0.16	0.05	—	0.09	0.09	0.09

G 35 basalt from the northern lava field-Pruvost; G 31 ignimbritic layer in the Pruvost caldera; G 28 hyperalcaline trachytic flow in the walls of Pruvost caldera; D 174 ignimbritic layer in the Pruvost strato-volcano; D 175, D 176, D 168 and D 169 glassy and microcrystalline lava flows in the Pruvost strato-volcano; CH 9 and CH 15 hyperalcaline pantelleritic trachyte and pantellerite of the recent obsidian flows and domes, south of Pruvost; D 217, D 224 and D 222 obsidian flows from Boina massif. CH 9 and CH 15 already published (Tazieff *et al.* 1969)

Strontium isotopic analyses

In table 6 the $^{87}Sr/^{86}Sr$ results for some samples of the Pruvost volcanic rocks are reported. A basalt sample yields the low ratio value of 0.7027. On the opposite side the alkaline acid rocks show a rather large variation range from 0.704 to 0.716. More detailed petrological studies and several other Sr isotopic analyses on the Pruvost rocks are needed in order to explain completely the causes of these $^{87}Sr/^{86}Sr$ ratio variations among the different samples. In any case the high ratios of the Pruvost ignimbrite and pantellerites suggest a significant contamination process with crustal material, or even a direct crustal origin, of these rocks.

The Sr isotopic analyses point out another important difference between the Pruvost massif and Erta'Ale range (see figure 12), i.e. between the two volcanic units which in this paper have been assumed as representative of the different volcanic groups in the northern Afar, respectively located in a marginal or subaxial position in the depression.

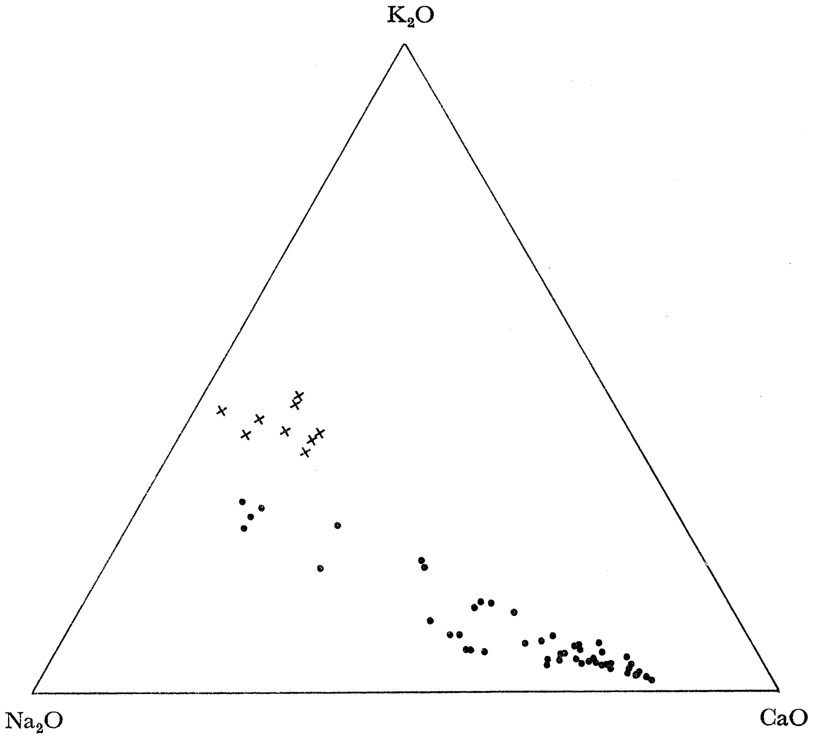

FIGURE 11. Na_2O–K_2O–CaO diagram for (×) P. Pruvost and (•) Erta'Ale volcanic rocks.

TABLE 6. PRUVOST MASSIF

samples	Rb (parts/10^6)	Sr (parts/10^6)	K/Rb	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$†
G 35, basalt	13	436.0	392	00.09	0.7027
G 28, hyperalkaline trachyte‡	—	—	—	—	0.7040
G 31, ignimbrite	180	34.5	212	15.1	0.7080
CH 15, pantellerite	139	10.5	307	38.2	0.7110
G 15, pantellerite	130	6.4	293	58.5	0.7158

† Normalized to $^{86}Sr/^{88}Sr = 0.1194$; $^{87}Sr/^{86}Sr$ ratio error is ± 0.001.
‡ Feldspar.

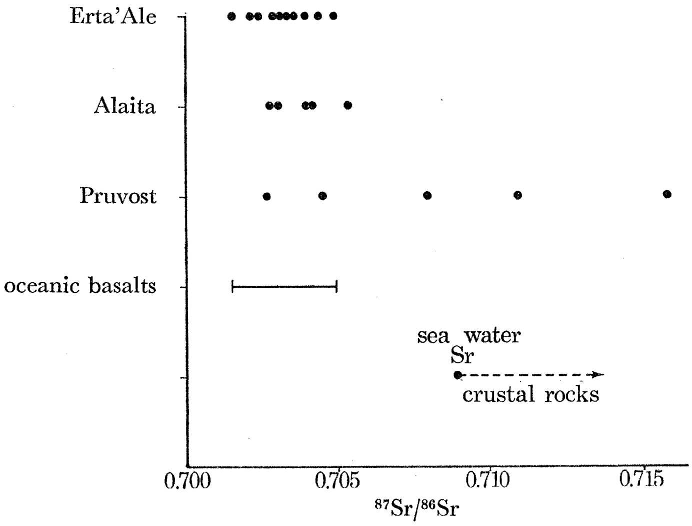

FIGURE 12. $^{87}Sr/^{86}Sr$ results for some volcanic rocks of the northern Danakil Depression.

CONCLUSIONS

The geological and volcanological data on the Erta'Ale range clearly demonstrate the existence of a fissural volcanism evolving towards the building of several central apparatuses, all located in the median zone of a tectonic depression. The oldest lava flows are to be seen on the borders and progressively became more recent towards the central axis of the depression, where several centres are still active. On the basis of petrological and Sr isotopic data all the volcanic rocks of this range can be considered as differentiation products of a subcrustal parental magma, not affected by contamination with crustal material.

From the discussed arguments the lack of sialic crust in the axial zone of the northern Danakil Depression (between the Salt Plain and the Lake Giulietti) is tentatively suggested. This trench has been probably formed by the drifting of the marginal blocks, particularly of the eastern one. This hypothesis is also supported by the lack of transversal tectonic features in all the area occupied by the volcanic range. The transversal tectonic features affecting the lower parts of the Ethiopian escarpment as well as the Danakil Alps, is probably the result of gravity readjustment of dislocated crustal blocks. They are therefore missing in the zones where the sialic crust is absent.

In the authors' opinion the Alayta unit is in all respects analogous to the Erta'Ale range, but in a stage of less advanced volcanological and magmatological evolution. Its origin is also probably related to a more recent laceration of the sialic crust.

The geological picture is notably different for the acid volcanic massifs located south of Giulietti Lake. The frequent existence of two tectonic trends, as well as the presence of large central volcanoes made up only by silicic rocks and built on fissural basaltic lava fields, already suggest the presence of sialic crust, perhaps reduced and thinned by tensional processes.

Several differences regarding the volume relations and the chemical and petrographical characteristics of the volcanic products of P. Pruvost unit, located near the Ethiopian escarpment, have been pointed out relatively to the axial volcanic ranges. The Sr isotopic results indicate a crustal origin or at least a notable contamination between subcrustal magmas and crustal material for some of the Pruvost rocks. The possibility of obtaining partial or total refusion of crustal material in the contact zones with subcrustal basic magmas has been proposed earlier by several authors (Daly 1914). A process of this kind could be active and important in the zones, where a lot of distensive fractures affecting the sialic crust gave rise to the uprising of large masses of subcrustal magmas, as here in the Afar depression.

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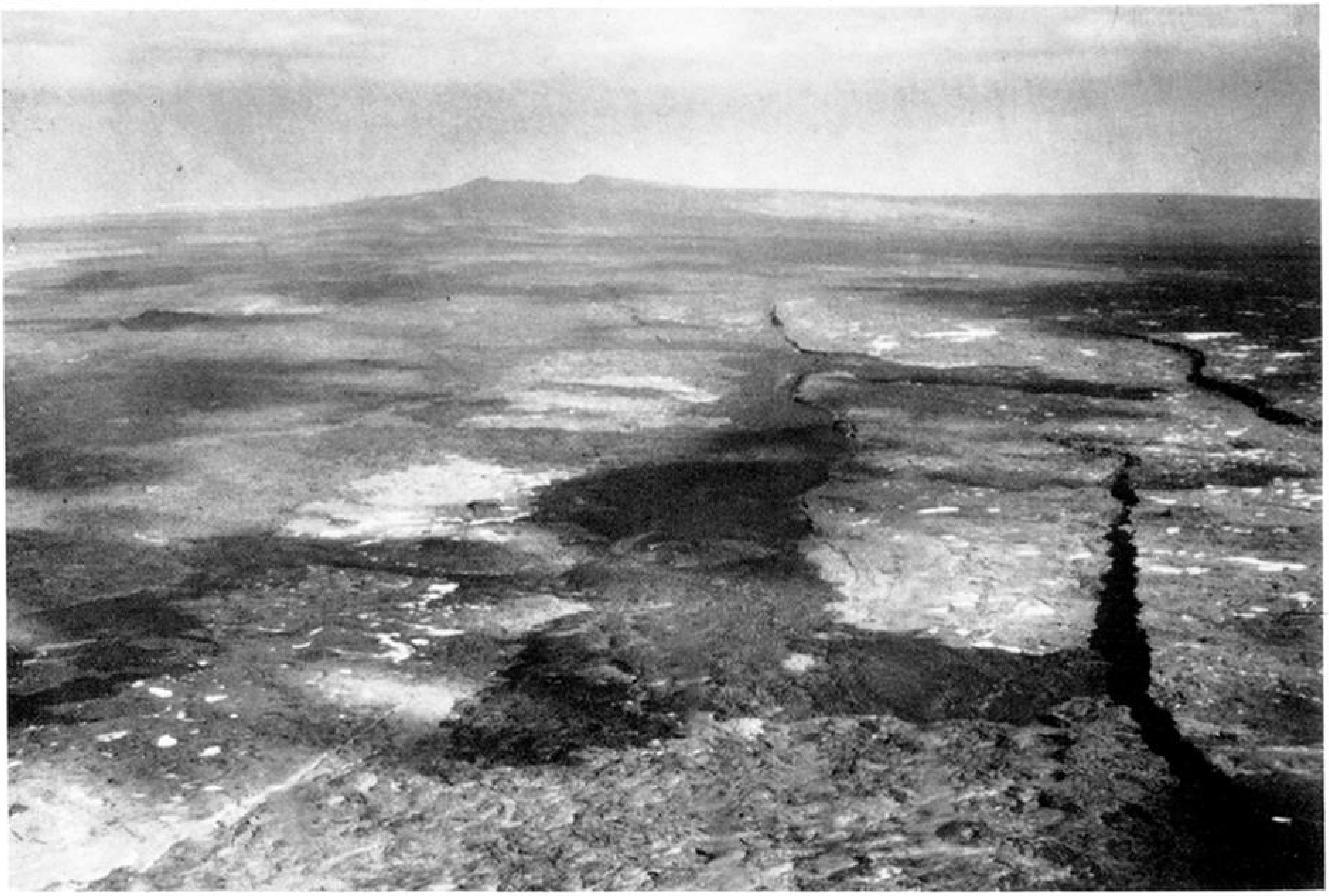

IGURE 3. NNW faults in the southwest of Erta'Ale range, at east of Lake Giulietti (at right).

IGURE 4. Southern part of Erta'Ale Range. A small 'graben' occupies the central part of the Range. The more recent flows are located in the median part.

FIGURE 5. NNW fissure, affecting an older strato volcano and generating basalt, in the centre of the range (Borale Ale).