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The Petrology of the Volcanic Rocks of South East King Island, Tasmania

By

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WITH 6 PLATES AND 2 TEXT FIGURES

ABSTRACT

Spilites and picrite basalts in the form of massive, pahoehoe, aa and pillow lavas comprise the greater part of a volcanic suite, presumed to be Middle Cambrian in age, which outcrops along the south eastern coast of King Island, Bass Strait, Tasmania, Australia. In the spilites the augite is unusually fresh and in the associated breccia fragments of undevitrified volcanic glass still exist. It has been suggested that some of the albite may be primary because of its ophitic relation and intergrowth with the augite. The results of both late magmatic and post magmatic alteration have produced an interesting assemblage of minerals including hydrogrossular which has not been described before in a similar context.

INTRODUCTION

The suite of volcanic rocks under consideration crops out along the south-east coast of King Island, Bass Strait, Australia. It extends for a distance of about 8 miles from Barrier Creek in the north to Grassy (latitude 40° 3′ S, longitude 144° 4′ E) in the south where it is probably terminated by a fault along the Grassy River.

The rocks dip about 40° to the east and strike approximately N. 10° E. Here and there they have been dislocated by small faults, striking usually about 290°-300°, which have prevented relatively accurate determination of the thickness of them. However, it is estimated that the volcanic suite has a greater thickness than 1000 feet.

The volcanic rocks are associated with tillite and varve. The greater part of the suite overlies these glacials but some of the basal members underlie them or are even interbedded with the varves.

Scattered over the island are outcrops of granite which seem to indicate that the whole island is underlain by this rock type. At Grassy the volcanic rocks have most probably been intruded by granite but unfortunately the contact has been concealed because of faulting and a recent covering of sand dunes.

AGE

In 1910 Debenham noted the occurrence of basalt south of the Fraser River and basic tuff at City of Melbourne Bay but ascribed a Tertiary age to them and correlated them with the Tertiary eruptives of Western Victoria. Then in 1915, Waterhouse recorded a brief description of an intensely altered series of basic and acid igneous rocks and igneous breccias and tuffs along the south-east coast of the island. He classed them tentatively as Cambro-Ordovician in age because of their similarity to the porphyroids on the West Coast of Tasmania. Because of the associated tillite and dolomitized varve, Carey (1946) correlated the series with the Zeehan glacials and Montana melaphyre volcanics of Tasmania and assigned them to the Pieman Group of rocks of Upper Proterozoic to Cambrian (?)

in age. At Dundas Trilobites, determined by Öpik* to be Upper Middle Cambrian in age, have been found in rocks interbedded with the Curtin Davis lavas reputed to be similar to those at Zeehan. West of Zeehan Trilobites, Brachiopods and Cystoids have been found in 'keratophyre tuffs' which overlie the Montana melaphyres and glacials. These fossils indicate an upper Middle Cambrian age for these rocks in this area. If the King Island volcanics are equivalent to those at Zeehan then their age may be stated as Upper Middle Cambrian.

However, the age of these volcanic rocks still remains a moot problem. No fossils have been found in the underlying sediments. If the age of the glacial beds is late Pre-Cambrian or very early Cambrian or even Upper Middle Cambrian then the volcanics are as old because they are so intimately related.

Although the presence of glass in the tuffs would seem to indicate a much younger age, the suite is definitely older than the granite, by which the rocks are affected, and this granite is most probably of lower Palaeozoic age.

Mode of Occurrence and Rock Types

In the field these volcanic rocks are quite striking and in spite of the great age which has been imposed upon them appear to be unusually fresh, so much so that they look as if they could have just issued from a volcano. This fact is well illustrated by the photographs in Plates I and II.

The forms of flow taken by the lavas are massive, one example showing columnar structure, aa or block, pahoehoe or ropy, and pillow. As well there is an accompanying group of fragmental rocks. Here and there narrow dykes intrude the suite. Generally speaking, the field form serves as a rough kind of classification for the rock types. Each form seems to have its own rock type with its particular kind of crystallization and mineral constituents. These will be described below.

The sequence of types overlying the glacials appears to be breccia and massive lava followed by aa, pahoeboe, and pillow, the resulting rock being in accordance with the prevailing conditions at the time of eruption. Showers of tuff were probably ejected throughout the period of vulcanicity.

Massive Lavas

These are normal flows of lava of varying thicknesses and seem to be the basal lavas of the series. Massive lavas occur below the glacial beds, interbedded with the varves and immediately overlying the glacials.

The rock is a spilite in composition and either appears as a normal looking basalt or a basaltic type with an extremely ophitic texture.

The type resembling a typical basalt (see Plate IV, figure 3) consists of laths of plagioclase and small grains of augite and magnetite. The plagioclase is almost pure albite, $Ab_{98}An_2$, and in parts shows alteration to chlorite and kaolin. The augite is surrounded by borders of a brown coloured mineral, otherwise it is relatively fresh. In some sections where the augite grains are larger, zoning and incipient hour-glass structure are present. Chlorite is abundant and appears in the interspaces of the plagioclase laths and augite granules. A little epidote in the form of small grains and patches of calcite, varying in abundance are also present. Sometimes small circular vesicles are present and these have been filled with chlorite and epidote.

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* Personal communication from Mr. M. R. Banks, palaeontologist, Geology Department, University of Tasmania who accompanied Dr. A. A. Öpik of the Bureau of Mineral Resources, Geology and Geophysics, Canberra, Australian Capital Territory, in the field. Stratigraphy from unpublished work of J. N. W. Elliston.

A coarser phase, doleritic in texture, but mineralogically the same, exists. Ilmenite is found surrounding patches of analcite. An interesting feature about this rock is that it shows evidence of slight metamorphism in the clouding of the felspar. Tiny needles of tremolite are found extending along the edges of the plagioclase crystals at right angles to the edges and pointing inwards.

The other type of massive lava is the one consisting of large plates of augite which are pierced by small laths of plagioclase. The augite is colourless, has good cleavage and is extremely fresh except for alteration to a brown mineral around the edges. The birefringence is ·030. The mineral is biaxial positive with an optic axial angle of 51° and an extinction angle of 40°. These properties indicate a diopsidic variety. Some of the large plates of augite have been so broken up by the presence of the plagioclase that they appear to consist of numerous small augite grains and it is not until the mineral is observed under analysed light that it is realized the mineral plate is homogeneous. This ophitic fabric is depicted in Plate V, Fig. 3. The plagioclase is albite and has been altered to sericite and contains patches of minute brown granules of hydrogrossular. Also present in the groundmass are granules of brown sphene, epidote, quartz, and calcite.

Another phase of this type of basalt gives rise to an unusual and interesting rock. Microscopically the rock consists for the most part of two minerals, diopsidic augite and a felspar which has been mostly pseudomorphed by sericite and some chlorite, although small patches of the unaltered albite remain. As usual the diopside is quite fresh and has similar properties as described above. Cleavage is strong and continuous and in some sections two at 90° are seen. The augite forms homogeneous plates which are broken only by the presence of the plagioclase.

The amazing feature of the rock is that the diopside and albite form perfect intergrowths covering the whole field of the microscope. (See Plate V, Figs. 1 and 2.) Occasionally between the areas of graphic intergrowth is to be found epidote. The author is unaware of a description of a similar phenomenon in the geological literature read.

Two questions are raised by the occurrence of such an intergrowth. First, is the structure an exsolution structure or secondly is it a true eutectic? The possibility of an exsolution structure can be neglected because the whole mass of rock is composed of such a structure and apparently is a feature of primary crystallization, probably formed at a later stage in crystallization following the formation of the ophitic fabric. This primary crystallization structure is the answer to the second possibility, that is a eutectic structure, and will be discussed in some detail later.

Pillow Lavas

These lavas have the typical ellipsoidal form of pillow lavas. The pillows vary from one to six feet in diameter. Each has a chilled margin of about half to one inch thick before a zone of radially arranged elongated vesicles filled with chlorite and other secondary minerals. Towards the centre the pillows show variolitic structure. Sometimes the material around the varioles has been weathered away leaving the varioles to stand out like marbles while at other times the varioles and surrounding material have weathered evenly, in which case the varioles are distinguished by their lighter colour. Examples of both types of weathering of varioles are shown in the photographs, Figs. 3 and 4 on Plate I. In some instances the surface of the pillow has a ropy structure.

The type of rock present is photographed in Plate IV, Fig. 4. It consists of a few idiomorphic laths of plagioclase up to 1 mm. in length and a few subidiomorphic phenocrysts of fresh augite in a groundmass of feathery augite and plagioclase and some granules of epidote and magnetite. The plagioclase is albite some of which shows no or only simple twinning. Some of the larger crystals show alteration in part to chlorite. Small vesicles lined with epidote and filled with chlorite are present. Other vesicles, lined with chlorite and/or epidote, are filled with quartz. The rock is traversed by very fine veins of secondary minerals, epidote, quartz, and calcite.

Pahoehoe (ropy) lavas

This lava type is found in irregular flows varying from 6 to 18 inches in thickness, each having a chilled surface and base. See Plate II, Figs. 3 and 4.) The surface of some flows reveals beautifully preserved ropy structure as illustrated in Fig. 3, Plate III. In the field some of the pahoehoe type of lava appears to be so contorted that it grades into the pillow type of lava. The chilled margin is about one inch in thickness and grades into a zone very rich in vesicles and then in some cases to a region of variolitic structure.

The crystallization of the pahoehoe lava varies from the surface of the flow towards the centre. The top section is very fine grained and contains minute crystals of augite and plagioclase with a few phenocrysts of olivine, now pseudomorphed by chlorite. Vesicles are very abundant and are mostly elongated more or less parallel to the top of the flow and average about 1·5 to 2 mm. in length. In some specimens the vesicles are circular or oval in shape, filled with chlorite and are so numerous that the name ‘ bile bean rock ’ has been given. This vesicular and fine grained type passes downwards into a type where vesicles are less numerous and olivine pseudomorphs are wanting. The augite and plagioclase have increased in size. The plagioclase is lath shaped and the augite is arranged in sheaf-like masses of radiating crystals. (See Fig. 2, Plate IV.) Most pahoehoe types fall into this general description but the alteration in some has been different.

In some, the vesicles have been filled by chlorite and epidote and in others by calcite, prehnite or albite. In most cases the plagioclase is albite and shows alteration to chlorite and hydrogrossular while the augite, on the other hand, has remained relatively fresh. Prehnite and sericite, albite, quartz, chlorite, epidote and hydrogarnet are to be found in the vesicles and interspaces in the coarser grained parts. It seems as though in the various pahoehoe lavas that either chlorite is the predominant infilling mineral when hydrogarnet is more abundant or prehnite when hydrogarnet is less abundant. Sometimes where the quartz has come in contact with the augite fine needles of tremolite, pointing into the quartz, are developed about the augite. Also there is a concentration of iron in the pyroxene along the tips of the crystals. Amongst the pahoehoe lavas is an excellent example of granules of hydrogrossular replacing olivine. (Plate VI, Fig. 3.) In some specimens some of the augite has been replaced by numerous tiny granules of pale green chlorite.

Aa (block) Lavas

These seem to merge from and into the pahoehoe and pillow lavas. Stray pillows, budding into each other by means of necks, as illustrated in Plate II, Fig. 1, are found amongst the block lavas. The blocks are irregularly shaped and vary in size, an average size being 4 to 5 inches. The surfaces are often irregular, shiny and iron stained. In general the block lava is a porphyritic rock consisting of phenocrysts of olivine, now pseudomorphed by almost colourless chlorite, in a very fine grained greyish coloured groundmass. (See Plate IV, Fig. 1.) The phenocrysts vary in size up to 1·3 mm. and in some cases are grouped together to give the rock a glomeroporphyritic texture. The crystals, on the whole, are idiomorphic and it was by the crystal outline and apical angle that the original mineral was determined to be olivine as there is no trace of the original mineral remaining. The form of the chlorite which is pseudomorphing the olivine is in aggregates of fibrolamellar structure. Its refractive indices were determined to be $\alpha = 1{\cdot}591$, $\gamma = 1{\cdot}594$. The mineral is biaxial positive and length slow. X-ray powder photography verified that it is of the pennine variety with the three strongest interplanar spacings being 7·146, 3·558 and 4·736. Pointing inwards from the sides of the chlorite and arranged haphazardly in the phenocrysts are needles of colourless to very pale green tremolite, ranging up to ·25 mm. in length. Some of the phenocrysts show patchy alteration to brown hydrogrossular. As illustrated by Fig. 4 on Plate VI. In other cases, however, the hydrogrossular has completely pseudomorphed the olivine crystals. In some sections it appears as if some pyroxene phenocrysts were present as well as olivine. These have been completely pseudomorphed by chlorite but definite cleavage traces still remain.

The groundmass is very fine grained, in some specimens probably devitrified glass, and is blotchy grey in colour. Under high power it is found to consist of fibrous needles of colourless tremolite and tiny patches showing incipient crystallization of pyroxene, most probably pigeonite. An attempt was made by X-ray powder photography to determine the type of pyroxene but many difficulties were encountered because of the nature of the mineral, its extremely fine crystallinity and its relationship with tremolite. However, a photograph was taken of the powdered groundmass and after elimination of the tremolite lines, the identity of the remaining mineral was determined as a clinopyroxene, possibly pigeonite. Because of its form the pyroxene gives anomalous optical properties. For the most part, the crystals are length slow, although some are length fast. It is optically positive with a rather small optic axial angle. After much difficulty the refractive indices were determined as $\alpha = 1{\cdot}629$ and $\gamma = 1{\cdot}653$ but the correctness of these cannot be vouched for due to the impossibility of separating the pyroxene from the tremolite. Persistent fringes of tremolite adhered to the pyroxene. Extinction appeared to be straight but again this may be due to the nature of the crystals.

In the groundmass and occasionally in the phenocrysts are to be found very small cubic crystals of the brown spinel, picotite.

Occasionally vesicles are found and these are filled with chlorite or hydrogrossular. When the latter mineral fills the vesicles it is darker towards the edge and very pale brown towards the centre as seen in Fig. 4 of Plate VI. The refractive index increases from the edge towards the centre.

Perhaps the 'shower droplet' rock could be described under this heading, not because it could be classed as a block lava but because it too is a picrite basalt as above. This 'shower droplet rock' occurs in a bed of about 2 feet thickness. It resembles a bed of conglomerate especially on a weathered surface but closer examination of a non-weathered section reveals a certain amount of welding together of the lapilli. Two photographs, Figs. 1 and 2, of this rock appear on Plate III. Apparently this rock type has developed close to the vent of the volcano and is the result of the accumulation of small drops of lava or lapilli which have dropped one on top of the other when almost, though not completely, solidified. Only one example has been found and it occurs just north of the outcrop of tillite north of Conglomerate Creek. Microscopically it contains idiomorphic phenocrysts of olivine pseudomophed by chlorite and brownish green coloured iddingsite along the cracks and around the edges. A few small oval shaped vesicles filled with chlorite, some of which is radiating, are present. The groundmass is so finely crystalline that it is impossible to distinguish the mineral constituents. Small crystals of picotite are present. Between the small lapilli of lava which average half an inch in diameter is to be found colourless to very pale green pleochroic chlorite.

Fragmental Rocks

Breccia and tuff are found interbedded with the lavas and also between some of the pillows where they are banded and are very tough. In keeping with the lavas they are green in colour.

Generally the breccia consists of fragments of glass which is light brown or green in colour. The fragments are often irregularly cracked and some have been altered to colourless chlorite or a very dark green fibrous variety, possibly garnierite, the nickel bearing chlorite. The presence of nickel is not surprising because tiny flakes of pale, copper pink coloured niccolite were found in varved shale on the southern headland of City of Melbourne Bay. Epidote crystals and granules are usually present and are abundant along cracks and boundaries of the glass fragments. In many cases the glass has been altered to dark brown hydrogrossular, the alteration usually commencing around the edges and proceeding inwards until the whole fragment has been altered as depicted in Plate VI, Figs. 1 and 2. Other pieces of the glass show complete devitrification to fine grained rock or in another case the glass seems to pass over to quartz crystals. In some of these glassy breccias a few pseudomorphs of chlorite and hydrogarnet after olivine are present, also some crystals of picotite.

The presence of glass in this volcanic suite is an unexpected feature because of its age and its resistance to hydrothermal solutions. Specimens have been found in which the glass is very dark green in colour, highly vitreous, and shows conchoidal fracture like obsidian. Its refractive index was determined as 1·6927 and its specific gravity as 2·49. The chemical composition of this glass will be discussed later.

The tuffs between the pillows and other banded tuffs are very fine grained and appear to consist of tiny fragmental grains of quartz, felspar and epidote and contain patches of calcite and chlorite.

Dyke Rocks

The volcanic suite is traversed by numerous small dykes which seem to trend roughly in a north south direction at right angles to the fault pattern. In all cases they are only about 2 to 3 feet wide and from a few yards to 100 yards at the most in length.

Petrographically, for the most part, the rock type is much the same as in the volcanic suite, particularly the massive basaltic variety. In some cases large phenocrysts of plagioclase, now kaolinised and sericitized are present. The rock in one dyke has been altered to an epidosite consisting of epidote, quartz and chlorite. Veins of idiomorphic to subidiomorphic crystals of epidote and quartz containing needles of tremolite are present.

There is one exception to the general rock type and this is an olivine minette. The rock contains large phenocrysts of brown biotite showing strong pleochroism and cleavage and colourless olivine and augite surrounded by reaction rims of what appears to be a pyroxene. This reaction rim in turn is surrounded by a halo of small magnetite granules. The augite is distinguished from the olivine by its strong cleavage. The groundmass is holocrystalline and contains abundant light brown biotite showing strong pleochroism and birefringence. Crystals of a mineral, most probably a pyroxene, judging from the crystallographic outline, are replaced by light green chlorite surrounded by magnetite granules. Orthoclase is abundant but is slightly altered to kaolin and has taken on a brownish colour. Magnetite as well as forming haloes about the altered minerals is scattered throughout the groundmass. Needles of tremolite and apatite are abundant, also small grains of calcite. Only one dyke of this rock was found and it trended in a similar direction to the fault pattern. Mineralogically this rock is a misfit in the spilitic suite. Minettes, according to Johannsen (1931) are usually associated with rocks of the granite-syenite family. As the volcanic series is intruded by granite in parts and closely underlain by it in others, it is most probably that this dyke rock is related to the granite rather than the volcanic rocks. A later age than the volcanics, that is, post faulting, is indicated by the direction of the trend of the dyke.

CHEMICAL COMPOSITION

According to the chemical analyses of the rocks there are two groups, a picrite basalt with a composition comparable with the intra Pacific or Oceanic type and a spilitic type.

Generally speaking the picrite basalts are those found in the pahoehoe and aa lavas and the spilites in the massive and pillow lavas.

In Table I the analysis of the picrite basalt is given and for comparison the average analyses of picrite basalt of Hawaii (Daly, 1933, p. 397) and oceanite of the world (Tyrrell, 1926, p. 131).

TABLE I.—ANALYSES OF PICRITE BASALTS

	I.	(*a*)	(*b*)
SiO_2	46·53	46·62	45·6
Al_2O_3	10·51	8·68	8·3
Fe_2O_3	·62	2·04	2·3
FeO	8·27	10·52	10·2
MgO	17·36	20·86	21·7
CaO	10·04	7·15	7·5
Na_2O	1·90	1·41	1·3
K_2O	·22	·28	·4
H_2O+	3·71		
H_2O-	·31	·23	·6
TiO_2	·21	1·71	1·7
P_2O_5	Tr.	·14	·3
Cr_2O_3	....	·12	....
MnO	·16	·14	·1
NiO	....	·10	....
Total	99·84	100·00	100·00
Norm			
Orthoclase	1·11		
Albite	16·24		
Anorthite	19·46		
Diopside	24·20		
Hypersthene	·33		
Olivine	33·02		
Magnetite	·93		
Ilmenite	·46		
Apatite	....		
Water	4·02		

I.—Picrite basalt (aa lava), King Island, Tasmania, Anal. B. Scott.
(*a*) Average picrite basalt of Hawaii according to Daly (1933) p. 397.
(*b*) Average oceanite of the world according to Tyrrell (1926) p. 131.

The spilitic types have been plotted on a triangular diagram (Fig. 2) on the basis of Na_2O, FeO and MgO (Sundius, 1930) and each of these rocks falls well within the area of spilites. The picrite basalt on the other hand falls well outside the area and on the true basalt side towards the base FeO, MgO of the diagram.

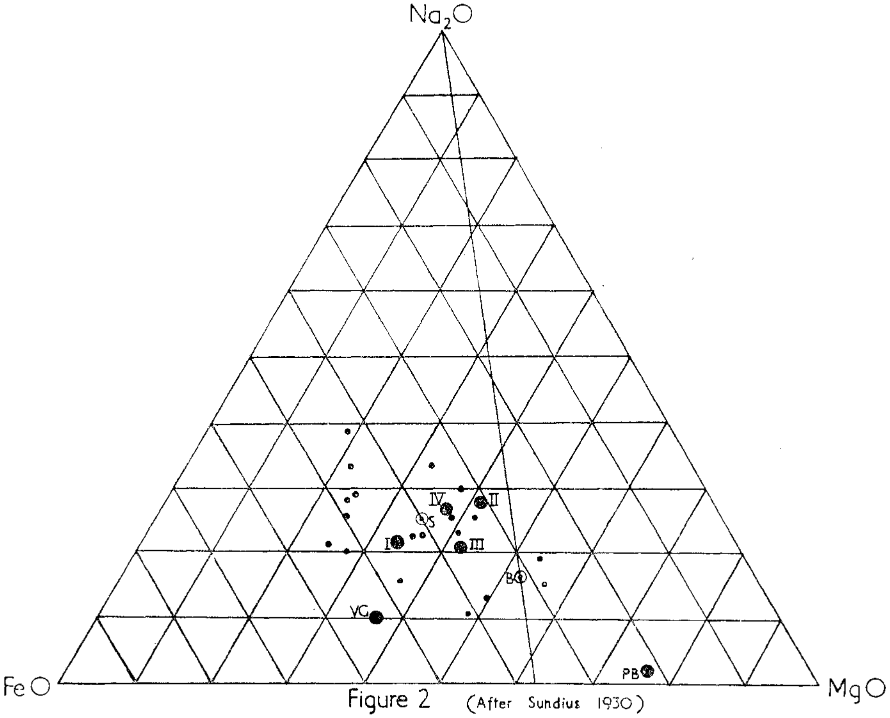

Figure 2 (After Sundius 1930)

- ● Spilites from various localities in the world as plotted on Sundius' original diagram
- ⊙ S Average Spilite
- ● I-IV King Island Spilites
- ○ PB Picrite Basalt King Island
- ● VG Volcanic Glass King Island
- ⊙ B Average Basalt

Four spilites were analysed and the results of the analyses are tabulated for comparison with those of a British spilite, an average spilite and two of Benson's (1915) in which the augite is also very fresh.

A glance at the analyses would indicate that the series is very rich in alumina, a fact which is illustrated again when the alteration of minerals is considered. The possible source of this alumina is discussed later. Low titanium is a feature of the rocks but nevertheless it is constant in the series. High potash in spilites I and II is probably due to the abundant sericitization of the felspar.

The analysis of the volcanic glass yielded an interesting result. It was hoped that the analysis showing the chemical composition of the glass would help to identify the nature of a parent magma of these lavas especially indicating whether it is a sodic or non sodic variety and at the same time to establish the fact as to whether the albite is primary or secondary. Contrary to expectation the glass is poor in the alkalis and magnesia but rich in lime and alumina for its silica content. Its position on the triangular diagram does at least indicate spilitic affinities. However, its composition does facilitate the explanation of some of the hydrothermal alteration. Perhaps the fact that this glass is so rich in lime helps to explain the stability of such an ancient glass.

TABLE II.—ANALYSES OF SPILITES

	I.	II.	III.	IV.	*(a)*	*(b)*	*(c)*	*(d)*
SiO_2	47·40	48·24	50·01	52·61	51·31	51·22	48·22	51·19
Al_2O_3	19·19	17·55	15·38	13·03	12·67	13·66	14·82	14·40
Fe_2O_3	1·48	1·05	4·86	3·90	·54	2·84	·56	4·43
FeO	8·26	7·04	9·21	8·48	7·99	9·20	9·25	9·04
MgO	3·60	5·27	5·85	5·10	2·19	4·55	5·58	4·51
CaO	11·25	10·43	6·35	7·26	8·17	6·89	8·81	6·05
Na_2O	3·40	5·58	4·77	5·60	5·21	4·93	4·95	4·18
K_2O	1·31	·97	·40	·42	·54	·75	·44	·78
H_2O+	3·32	2·88	2·60	1·65	·04	1·88	2·54	1·82
H_2O-	·34	·17	·23	·10	2·31		·15	·24
TiO_2	·29	·70	·73	·72	1·92	3·32	2·68	2·69
MnO	·13	·12	·21	·19	·45	·25	·23	·21
P_2O_5	n.dt.	·10	·09	Tr.	·90	·29	·24	·40
CO_2	....	·11	·13	·05	6·15	·94	1·40	abs.
S	....	....	....	·08	....	....	....	....
FeS_2	....	....	....	....	·30	....	·37	·19
Fe_7S_8	....	....	....	....	·17	....	....	...
NiO	....	....	....	....	....	....	·03	—
Total	99·97	100·21	100·82	99·19	100·86	100·72	100·26	100·13

Norms	I.	II.	III.	IV.
Orthoclase	7·78	6·12	2·22	2·22
Albite	18·34	19·65	40·35	46·63
Anorthite	33·08	20·02	19·46	10·01
Nepheline	5·68	14·91	....	·28
Diopside	19·15	24·76	8·96	21·99
Hypersthene	....	....	7·20	....
Olivine	19·05	7·74	11·18	9·76
Magnetite	2·09	1·62	6·96	5·57
Ilmenite	·61	1·37	1·37	1·37
Pyrite	....	....	....	·04
Apatite	....	·34	·34	....
Calcite	....	·20	·20	·30
Water	3·66	3·05	2·83	1·75

I. Spilite (Intergrowth type), King Island, Tasmania, Anal. B. Scott.
II. Spilite (Ophitic type), King Island, Tasmania, Anal. B. Scott.
III. Spilite (Basaltic type), King Island, Tasmania, Anal. B. Scott.
IV. Spilite (Pillow lava), King Island, Tasmania, Anal. B. Scott.
(a) Spilite, West side of Tayvallish Peninsula, Argyllshire. Anal. D. G. Radley (Dewey & Flett (1911))
(b) Average spilite according to Sundius (1930), p. 9.
(c) Spilite Frenchman's Spur, Nundle, N.S.W., Benson (1915), p. 139.
(d) Quartz dolerite, Munro's Ck., N.S.W., Benson (1915) p. 139.

TABLE III.—ANALYSES OF VOLCANIC GLASS

	I.	(*a*)
SiO_2	44·14	47·57
Al_2O_3	15·63	14·85
Fe_2O_3	5·45	4·52
FeO	·93	8·28
MgO	2·75	7·33
CaO	20·44	8·99
Na_2O	·80	3·93
K_2O	·21	1·03
H_2O+	6·04	1·70
TiO_2	·31	1·61
MnO	·11	....
P_2O_5	n.dt.	·28
Total	100·81	100·09
Norm.		
Quartz	16·50	
Orthoclase	1·11	
Albite	6·81	
Anorthite	38·36	
Diopside	17·62	
Wollastonite	7·08	
Ilmenite	·61	
Magnetite	7·89	
Water	6·04	

I. Glass from breccia, King Island, Tasmania, Anal. B. Scott.
(*a*) Average analysis of 5 basaltic glasses from Washington (1917).

Identification of the fine grained tuff between the pillows was difficult microscopically because of the fineness of grainsize. However, chemical analysis has revealed that the rock is definitely a tuff of similar composition to its parent lavas and is not a banded chert, rich in silica, as one may be inclined to think because of its extreme toughness, hardness and field position.

$Si0_2$	51·14
Al_2O_3	9·01
Fe_2O_3	2·32
FeO	3·99
MgO	12·49
CaO	14·34
Na_2O	1·67
K_2O	·39
H_2O+	2·64
H_2O-	·20
TiO_2	·49
MnO	·16
P_2O_5	ndt.
CO_2	·13
Total:	99·74

Tuff, Between Pillows of Lava, King Island, Tasmania, Anal. B. Scott.

TRACE ELEMENTS

Spectrographic analyses for trace elements were carried out on several of the analysed rock specimens in the Department of Mineralogy and Petrology, University of Cambridge.

The results of these spectrographic analyses have been combined with the corresponding analyses and are tabulated in Table IV.

The amounts of each trace element are fairly constant in the volcanic suite and in keeping with the basicity of the rocks. They compare favourably with those in other rocks.

Chromium and nickel are low in the basaltic pillow lava varieties of spilites while copper is high in the pillow lava. Barium is highest in the ophitic type of spilite. The absence of tin is surprising. Has this tin been removed by hydrothermal solutions or was it originally absent?

TABLE IV.—TRACE ELEMENTS IN KING ISLAND ROCKS (Expressed in parts per million)

	I.	II.	III.	IV.	V.	(*a*)	(*b*)	(*c*)
SO_3	....	....	....	....	....	1,200	....	....
P_2O_5	...	1,000	900	....	....	2,400	700	2,800
SiO_2	465,300	482,400	500,100	526,100	511,400	485,000	504,200	482,400
Al_2O_3	105,100	175,500	153,800	130,300	90,100	130,100	165,500	178,800
Ga_2O_3	*(<_6_)	_13_	_20_	_13_	_20_	_30_	_30_	_10_
Cr_2O_3	_804_	_329_	_29_	_44_	_659_	_2,000_	_600_	_500_
TiO_2	2,100	7,000	7,300	7,200	4,900	10,300	8,400	9,700
V_2O_3	_115_	_257_	_257_	_404_	_110_	_500_	_450_	....
Fe_2O_3	6,200	10,500	48,600	39,000	23,200	14,300	5,200	31,600
Li_2O	_43_	_258_	_108_	_22_	_108_	_40_	_10_	_20_
MgO	173,600	52,700	58,500	51,000	124,900	129,100	73,100	75.000
NiO	_573_	_127_	_38_	_89_	_255_	_250_	_100_	_200_
CoO	_57_	_32_	_46_	_46_	_32_	_90_	_35_	_100_
CuO	_69_	_75_	_313_	(>_313_)	_31_	_200_	_200_	....
FeO	82,700	70,400	92,100	84,800	39,900	91,700	96,100	59,500
ZnO	....	....	....	....	....	_60_	_70_	....
Sc_2O_3	_30_	_54_	_54_	_54_	_23_	_30_	_15_	_30_
ZrO_2	*	_20_	_40_	_40_	_27_	....	....	....
MnO	1,600	1,200	2,100	1,900	1,600	1,900	700	1,300
Na_2O	19,000	55,800	47,700	56,000	....	20,300	15,600	25,500
Yt_2O_3	*(<_13_)	_19_	_25_	_38_	*(<_13_)	....	....	_3_
CaO	100,400	104,300	63,500	72,600	143,400	95,200	123,200	109,900
ThO_2	....	....	....	....	....	_30_	_60_	....
La_2O_3	*	*	*	*	*	....	....	....
SnO	*	*	*	*	*	_200_	_350_	_200_
PbO	*	*	*	*	*	....	....	....
K_2O	2,200	9,700	4,000	4,200	....	4,500	1,900	8,900
BaO	*(<_5_)	_558_	_56_	_5_	_112_	_80_	_200_	_70_
Rb_2O	*(<_10_)	_109_	*(<_10_)	*(<_10_)	*(<_10_)	_20_	_20_	_20_

I. Picrite basalt, King Isand.
II. Spiite (ophitic type), King Isand.
III. Spilite (basaltic type), King Island.
IV. Spilite (pillow lava), King Island.
V. Banded tuff, from between pillows, King Island.
(*a*) Olivine basalt, centre of dyke, Poortji (Frankel, 1942 p. 18).
(*b*) Dolerite, Kohstaol type, Execution Rock Sill (Walker and Poldervaart, 1949 p. 286).
(*c*) Average gabbro, according to Wager and Mitchell, 1943, p. 286.
Roman type—determined by chemical analyses.
Italics—determined spectrographically.
....—not recorded.
*—present below sensitivity limit.

Hydrothermal Alteration

This particular section of the study of the petrology of these lavas is the most interesting, not only because it introduces an extremely interesting assemblage of minerals but because the origin of the solutions responsible for the changes is controversial.

Before proceeding to describe the types of alteration it would be advisable to define the term 'hydrothermal' as used by the author as nomenclature in this field is rather confusing and conflicting. In this paper the term is used in the same sense as used by Shand (1944) when he proposed that high temperature hydrothermal be the stage between 700°-300° C and low temperature hydrothermal below 300° C and the term to be all embrasive in that it includes the effects of late magmatic alteration or alteration by extraneous solutions.

Hydrogrossular—a New Occurrence

Several occurrences of garnets associated with rocks of basic and ultrabasic intrusions have been recorded. Hutton (1943) pointed out that the mineral described as grossularite in the rodingites of New Zealand is not a true calcium garnet but one of the hydrogarnets belonging to the isomorphous series, tricalcium aluminate hexahydrate—grossularite. Yoder (1950), in his recent investigation on the stability of grossularite, suspects that the majority of naturally occurring garnets described as grossularite contain some hydroxyl groups. He is of the opinion that the dry end member of the grossularite—$Ca_3Al_2(OH)_{12}$ series does exist but that it cannot exist in the presence of water at elevated temperature.

Occurrence:—Hitherto a similar type of occurrence of hydrogrossular has not been described. As mentioned above, all examples have been from intrusive rocks. However, in 1910 Fenner described the occurrence of garnet as a secondary mineral in the Watchung basalt where it has been derived from olivine, felspar and diopside. Fenner writes 'This mineral has not heretofore been recognised under exactly similar circumstances, so far as the writer is aware'. This description appeared before the existence of a hydrogarnet series was established but no doubt if the garnets were studied in light of recent information it would prove to be a member of the grossularite—$Ca_3Al_2(OH)_{12}$ series.

In these basic volcanic rocks under consideration the hydrogrossular is definitely secondary. As previously mentioned it is found to be pseudomorphing almost perfect idiomorphic phenocrysts of olivine (see Plate VI, Fig. 3) and in some cases the plagioclase. It is also found in veins and vesicles (see Plate VI, Fig. 4). A great proportion of the glass in the breccias has been converted to hydrogarnet. Some pseudomorphs of chlorite after olivine show the presence of hydrogrossular along cracks and/or in a patchy fashion towards the centre. The hydrogarnet replacing the olivine and plagioclase is in the form of tiny granules and not one large crystal. In the vesicles and veins it has a concretionary form and the various members of the hydrogarnet series can be recognized by the differently coloured concentric layers and varying refractive indices. In some rocks the hydrothermal solution containing this mineral has attacked the groundmass, thus converting it into hydrogarnet, as illustrated in Fig. 4 on Plate VI. This hydrogarnet is more abundant in the picrite basalts than the spilites but in the latter some of the augite shows alteration around the edges to a brown coloured material. There is a possibility that this material may be one of the early phases during the garnetising process.

Properties:—The Hydrogrossular varies from dark brown to very pale brown or almost colourless.

The refractive index also varies from 1·663 to 1·753 according to the water content. It is interesting to note that in the vesicles the refractive index of the various layers increases from the edge inwards, commencing with a rather hydrous layer with low refractive index and grading into an almost anhydrous member of the series.

For the most part, the mineral is isotropic but some sections show very low birefringence.

Chemical Composition:—Owing to the nature of the mineral it was impossible to separate the various members of the series present so a chemical analysis was made on an average powder.

For comparison several other analyses have been tabulated in Table V.

TABLE V.—ANALYSES OF HYDROGROSSULAR

	I.	(*a*)	(*b*)	(*c*)	(*d*)
SiO_2	37·28	34·48	37·60	36·05	38·8
Al_2O_3	23·11	19·87	22·15	25·79	22·66
Fe_2O_3	5·26	0·61	·50	nil	1·75
FeO	0·73	0·85	·55	·56	....
MgO	4·12	2·07	tr.	·15	·68
CaO	27·44	37·40	38·40	35·72	35·00
Na_2O	....	0·02	tr.	·13	....
K_2O	....	0·01	tr.		....
H_2O+	1·37	4·65	1·20	1·10	....
H_2O-	0·44	0·23	·20	....	....
TiO_2	0·06	0·03	·10	·03	....
MnO	n.dt.	·02	tr.	·15	·30
Cr_2O_3	n.dt.	n.dt.	·10	....	....
Total	99·81	100·24	100·95	99·68	99·19

I. Hydrogrossular, King Island, Tasmania, Anal. B. Scott.
(*a*) Hydrogrossular, Champion Ck., Waimea, New Zealand, Anal. F. T. Seelye, (Hutton, 1943, p. 74).
(*b*) Green "Jade", Buffelsfontein, Anal. H. G. Weall (Hall, 1924, p. 48).
(*c*) Grossularite, Roding River, Dun Mt., New Zealand, Anal. Dominion Lab. (Grange, 1927, p. 165).
(*d*) Green Grossularite, Dana's System of Mineralogy.

An interpretation of the analysis of the King Island hydrogarnet showing the amounts of the various garnet molecules is given below.

Andradite	16·81
Tricalcium aluminate hexahydrate	4·73
Grossular	53·22
Almandine	1·83
Pyrope	13·97
Silica	3·38
Corundum	4·91

The chemical composition based on the general formula $X_3Y_2(ZO_4)_3\text{-m}(OH)_4\text{m}$ (McConnell, 1942), of this particular hydrogarnet has been determined as $(CaMgFe'')_{2\cdot631}\ (AlFe'''Ti)_{2\cdot068}\ ((Si,Al)O_4)_{2\cdot833}\ (OH)_{\cdot667}$.

The valency of the formula was balanced by taking into consideration that $(OH)^{-1}$ replaces $(O)^{-2}$ of the SiO_4, leaving empty spaces.

In this case it was necessary to allot some alumina to the ZO_4 group where it occupied the empty spaces. Alderman (1935) pointed out that this was also necessary in his case when dealing with almandine garnets.

TABLE VI.—CALCULATION OF FORMULA OF HYDROGROSSULAR

Oxides	Weight %	Molecular Proportions	Ionic Ratios	Positive Ions
SiO_2	37·28	·621	·621	2·761
Al_2O_3	23·11	·226	·452	2·010
Fe_2O_3	5·26	·033	·066	·293
FeO	·73	·010	·010	·044
MgO	4·12	·103	·103	·458
CaO	27·44	·490	·490	2·179
H_2O+	1·37	·075	·150	·667
TiO_2	·06	·001	·001	·004

$$\left.\begin{array}{ll}\text{Ca} & 2\cdot179\\ \text{Mg} & \cdot458\\ \text{Fe}'' & \cdot044\end{array}\right\} 2\cdot681 \qquad \left.\begin{array}{ll}\text{Al} & 1\cdot771\\ \text{Fe}''' & \cdot293\\ \text{Ti} & \cdot004\end{array}\right\} 2\cdot068 \qquad \left.\begin{array}{ll}\text{Si} & 2\cdot761\\ \text{Al} & \cdot239\end{array}\right\} 3\cdot000 \qquad \left.\begin{array}{ll}\text{OH} & \cdot667\\ \text{O} & 11\cdot333\end{array}\right\} 12\cdot000$$

Valency balance:

Excess positive		Deficit positive	
$\overset{-1}{(OH)}$ in place of $\overset{-2}{(O)}$	·677	$\overset{+3}{Al}$ in place of $\overset{+4}{Si}$	·239
$\overset{+4}{Ti}$ in trivalent group	·004	Empty divalent spaces 2(3·000—2·681)	·638
Excess trivalent group	·068		
Total	·875		·877

According to Flint, McMurdie and Wells (1941) silica can replace water in both $3CaO,Al_2O_3,6H_2O$ and $3CaO,Fe_2O_3,6H_2O$ so that the end products become grossularite and andradite respectively. Chemically 6 molecules of H_2O are interchangeable with 3 molecules of SiO_2. The replacement, from a structural point of view, was explained by McConnell (1950) when in dealing with the crystal chemistry of montmorillonite, he likened the replacement of silica by water to the similar case of the hydrogarnets. He demonstrated that $(OH)_4$ has a stable configuration as discrete tetrahedra and 4H becomes equivalent electrostatically to Si in the structure.

X-Ray Data:—An X-ray powder photograph of the hydrogrossular was taken on a 9 cm. Unicam camera, using copper radiation and a nickel screen. X-ray data are given in Table VII.

Albite

Albite appears in these rocks as a complete replacement of a more basic plagioclase and in vesicles where it is associated with chlorite and has a pink colour in hand specimen.

Its refractive index is less than Canada Balsam and in the sections belonging to the zone normal to the 010 face the maximum extinction angle is 18½° indicating a composition of $Ab_{98}An_2$, almost pure albite. Sometimes the albite shows well defined lamellar twinning but at others it is untwinned. When untwinned in the vesicles it is difficult to distinguish it from quartz, the only means of distinction often being by the biaxial positive figure of albite as opposed to the uniaxial positive one of quartz. Often the albite shows secondary alteration to sericite, kaolin and chlorite.

TABLE VII.—INTERPLANAR SPACINGS OF HYDROGROSSULAR FROM KING ISLAND

h k l	d	Intensity	θ in degrees
110	7·195	*	6·151
220	4·303	*	10·321
222	3·572	*	12·462
400	3·026	****	14·761
420	2·689	****	16·600
332	2·563	**	17·504
422	2·460	***	18·265
431 ; 510	2·361	**	19·058
521	2·200	**	20·517
532	1·951	**	23·276
620	1·908	*	23·894
444	1·735	*	26·384
640	1·672	***	27·462
642	1·607	****	28·667
732 ; 651	1·539	*	30·062
800	1·503	**	30·855
840	1·344	**	34·994
842	1·313	**	35·945
664	1·283	*	36·944
864	1·116	**	43·667
10,4,2	1·110	**	44·603
880	1·063	*	46·506
10,71 ; 10,55	·978	**	52·055
12,60 ; 10,84	·897	*	59·302
14,40 ; 12,66	·826	*	68·958
14,42 ; 12,66 10,10,4	·818	*	70·386

****=very strong ; ***=strong ; **=weak ; *=very weak.

Strangest lines d=2·689, 1·607, 3·026.

Calculation of the size of the unit cell using the formula $a=\frac{\sqrt{h^2+k^2+l^2}\,\lambda}{2\sin\theta}$ was determined to be 12·031A° when $\theta = 68{\cdot}958°$ and 12·030A° when $\theta = 70{\cdot}386°$. The unit cell size of 12·03 for this hydrogarnet lies within the range 11·84A° for grossularite to 12·56A° for tricalcic aluminate hexahydrate given by Flint, McMurdie and Wells (1941).

As mentioned in the petrographical description of the rock types albite is found as an intergrowth and the ophitically arranged with fresh diopsidic augite. It may well be, under such circumstances, that the albite is primary and not secondary but this point will be discussed later. The fact remains that some, if not all, of the albite is definitely secondary.

Chlorite

Chlorite, perhaps, is the most common of the secondary minerals. It occurs in all the rocks, where it is found to replace or partly replace olivine, augite and plagioclase and to occupy vesicles and veins.

The chlorite varies from a colourless to rather dark green variety. Even in the same vesicle there has been known to be two different varieties. X-ray powder photography has shown that the chlorites do vary. The chlorite pseudomorphing olivine is generally of the colourless variety while that in the vesicles is of various shades of green. The most common variety is pennine.

The form of the chlorite pseudomorphing the olivine is in aggregates of fibrolamellar structure. It has a low birefringence of ·003 and the interference colours range from black and grey to anomalous colours. The refractive indices are $\alpha = 1{\cdot}591$, $\gamma = 1{\cdot}594$. The mineral is optically positive and is length slow. According to X-ray photography the three strongest interplanar spacings are d = 7·146, 3·558, 4·736. The green chlorite common in the vesicles is pleochroic. It, too, is optically positive and shows interference colours grading from grey to anomalous blue. Its refractive indices are higher than those of the colourless variety and are $\alpha = 1{\cdot}624$, $\gamma = 1{\cdot}629$. Most probably this chlorite is a variety of pennine too.

Epidote

Like chlorite, epidote is rather abundant and usually occurs as small granules or idiomorphic crystals in vesicles and veins, often lining the vesicles for chlorite. It is colourless to pale green and is slightly pleochroic. In some cases it shows twinning. It is distinguished from the diopsidic augite by its straight extinction.

Tremolite

Tremolite is very common in the series and occurs in all types of lava, aa, pahoehoe, and the massive type. It is almost colourless to very pale green with low birefringence and a maximum extinction angle of 20°. It replaces plagioclase in the block lava and commonly replaces or partly replaces augite in the massive lava towards the granite contact at Grassy. In some of the pahoehoe lavas it occurs in a peculiar intergrowth fashion with augite where it may be partially replacing that mineral or even replacing plagioclase. There is no evidence on which to decide. In the block lava it is also associated with chlorite in pseudomorphing the olivine and in the vesicles.

Prehnite

Prehnite occurs in the vesicles of some of the pahoehoe and pillow lavas. In hand specimens it is generally white with a greenish tinge. It is often in radiating form and shows typical bow-tie structure. It is length slow and has a double refraction of about ·02.

Sericite

This mineral is fairly common as a replacement of albite. However, it is found, too, sometimes lining the vesicles for prehnite or occurs as flakes with the prehnite.

The presence of sericite in the latter context was unexpected. At first this flaky mineral in the vesicles was considered to be either talc or pyrophyllite, which have similar optical properties to muscovite, as the assemblage of minerals was more in keeping with either of these, plus the fact that alumina and magnesia bearing solutions had been at work. However, after much difficulty a tiny fragment was separated from the prehnite and this was treated as a powder fragment because of its fine flaky nature and an X-ray photograph was taken. Photographs taken on small diameter cameras failed to distinguish the mineral from either talc or pyrophyllite but the photograph taken on a 19 cm. Unicam camera, when the lines were more spaced, definitely indicated that the mineral is sericite.

Calcite

One would expect to find more of this mineral than is actually present. It is found, however, in vesicles and veins. It is possible that the temperature conditions were too high for its formation in abundance.

Quartz

Quartz, like calcite, is not over abundant. It is only found in vesicles and veins and in the epidosites at Grassy.

Discussion

An examination of the chemical analyses and the mineral assemblage of the rocks indicate a great richness in alumina. The following questions arise. What is the origin of this constituent? Was it derived from a rich aluminous magma and the alteration the result of percolating late stage magmatic solutions, or was it derived from an external source and therefore the alteration the result of the invasion of the solidified lavas by foreign solutions?

The late magmatic stage alteration can be supported. The following equations indicate that the present mineral constituents could have been derived from a lava in which there has been a rearrangement of constituents, once the 'spilitic reaction' had commenced, that is assuming that the plagioclase was a more basic variety originally.

Each type of lava will be considered and the supposed original constituents will be taken into consideration.

Pahoehoe lava

(*a*) in which chlorite is the predominant secondary mineral

$$\begin{array}{l}\text{Olivine}\\ \text{Basic plagioclase}\\ \text{Pyroxene}\end{array} \longrightarrow \begin{array}{l}\text{Chlorite, Hydrogrossular}\\ \text{Albite, Chlorite, Hydrogrossular}\\ \text{Pyroxene}\end{array}$$

$$1.\ \overset{\text{Anorthite}}{2CaAl_2Si_2O_8} + Na_2O + 2SiO_2 \longrightarrow \overset{\text{Albite}}{2NaAlSi_3O_8} + 2CaO + Al_2O_3$$

$$2.\ \underset{\text{Anorthite}}{CaAl_2Si_2O_8} + 2CaO + SiO_2 \longrightarrow \underset{\text{Grossular}}{Ca_3Al_2(SiO_4)_3}$$

$$3.\ \underset{\text{Olivine}}{3Mg_2SiO_4} + 4H_2O + Al_2O_3 \longrightarrow \underset{\text{Chlorite}}{Mg_5Al(OH)_8(Al,Si)_4O_{10}} + MgO$$

$$4.\ \underset{\text{Olivine}}{Mg_2SiO_4} + 3CaO + Al_2O_3 + 2SiO_2 \longrightarrow \underset{\text{Grossular}}{Ca_3Al_2(SiO_4)_3} + 2MgO$$

$$5.\ \underset{\text{Anorthite}}{CaAl_2Si_2O_8} + 5MgO + 4H_2O + SiO_2 \longrightarrow \underset{\text{Chlorite}}{Mg_5Al(OH)_8(Al,Si)_4O_{10}} + CaO$$

(*b*) in which prehnite is the predominant secondary mineral

$$\begin{array}{l}\text{Basic plagioclase}\\ \text{Pyroxene}\\ \ \end{array} \longrightarrow \begin{array}{l}\text{Albite, Chlorite, Grossular}\\ \text{Chlorite, Pyroxene}\\ \text{Prehnite, Quartz in vesicles}\end{array}$$

Equations 1, 2 and 5 as above.

$$3CaO + Al_2O_3 + H_2O + 3SiO_2 \longrightarrow \underset{\text{Prehnite}}{H_2Ca_2Al_2Si_3O_{12}}$$

Spilitic lavas (massive and pillow types)

Equations as for (*b*) except epidote formed more readily than prehnite.

$$4CaO + 3Al_2O_3 + 6SiO_2 + H_2O \longrightarrow \underset{\text{Clinozoisite}}{2Ca_2Al_3(SiO_4)_3OH}$$

Aa lava

$$\begin{array}{l}\text{Olivine}\\ \text{Basic plagioclase}\\ \text{Pyroxene}\end{array} \longrightarrow \begin{array}{l}\text{Chlorite, Hydrogrossular}\\ \text{Tremolite}\\ \text{Pyroxene}\end{array}$$

$$\underset{\text{Olivine}}{3Mg_2SiO_4} + 4H_2O + Al_2O_3 \longrightarrow \underset{\text{Chlorite}}{Mg_5Al(OH)_8(Al,Si)_4O_{10}} + MgO$$

$$\underset{\text{Anorthite}}{2CaAl_2Si_2O_8} + 3MgO + 4SiO_2 + H_2O \longrightarrow \underset{\text{Tremolite}}{Ca_2(Mg,Al)_5(OH)_2(Si_4O_{11})_2} + Al_2O_3$$

$$3CaO + Al_2O_3 + 3SiO_2 \longrightarrow \underset{\text{Grossular}}{Ca_3Al_2(SiO_4)_3}$$

The late magmatic theory, however, appears to break down when it is realised that the tuffs, too, have been subjected to a similar alteration process. Even the glass fragments which had been completely solidified so that no late stage solutions could have remained have succumbed in places to hydrothermal alteration. A close study of the analyses of the volcanic glass and hydrogrossular may give a clue to this problem.

TABLE VIII.—ANALYSES OF VOLCANIC GLASS AND HYDROGROSSULAR

	Volcanic Glass	Hydrogrossular (Altered glass)	Constituents gained during alteration
SiO_2	44·14	37·28	
Al_2O_3	15·63	23·11	X
Fe_2O_3	5·45	5·26	
FeO	4·93	·73	
MgO	2·75	4·12	X
CaO	20·44	27·44	X
Na_2O	·80	....	
K_2O	·21	....	
H_2O	6·04	1·81	
TiO_2	·31	·06	
MnO	·11	n.dt.	
Total	100·81	99·81	

Apparently this change involved an introduction of alumina, lime and magnesia. From this evidence it seems that the source of these constituents is external but where could this source be? In the introduction to this paper it was mentioned that the volcanic suite is intruded by granite at Grassy. This may be the answer to the question for not only do Nye and Knight (1943), in their report on the King Island scheelite mine at Grassy, report an introduction of alumina and lime in the interchanges of material during mineralization but the lavas apparently closer to the granite show a greater degree of hydrothermal alteration. Here the pyroxene of the lavas is practically wholly converted to tremolite. The plagioclase is albite and in some cases has been partially replaced by sericite, chlorite and hydrogarnet. Epidote and iron ore granules are abundant. Abundant veins and vesicles of pink albite and chlorite and sometimes quartz are very common and it is not unusual to find large patches of the lava converted to an epidosite, i.e., epidote, albite and quartz rock with abundant iron ore. The presence of tremolite would indicate that these lavas are not in the inner part of the contact aureole but in the outer, for according to Harker (1939) tremolite is not stable at high temperatures.

Further evidence to support the idea that constituents may have been gained from the granite is provided by the glacial tillite and varves. These rocks have been haematitized and dolomitized to a considerable extent. Sometimes the tillite is haematitized and the varves overlying it dolomitized. At other times most of the varves are haematitized as well and the dolomitization is not noticed. This is possibly due to the magnesia being lost to the overlying lavas and being incorporated in the formation of new minerals such as tremolite and chlorite. Unfortunately it has not been possible to trace the iron and magnesia rich zones consistently in the lavas because of the faulting which postdated the granite. Field evidence is consistent with the idea that a magnesia front is preceding an iron front. There is ample evidence of magnesia having been gained by the lavas but iron is not over abundant as evidenced by the formation of tremolite rather than actinolite and the almost colourless variety of chlorite. However, some perfect cubic crystals of iron pyrities are sometimes present in the lavas but these are often quite abundant in the dolomitized varves.

The temperature at which this hydrothermal alteration was achieved must be considered. The presence of such a hydrogarnet, containing a small amount of water, indicates that fairly high temperature hydrothermal conditions prevailed.

Yoder (1950), as a result of preliminary experimental work, tentatively states that members of the hydrogrossular series form in the presence of water at a temperature under approximately 750° C at atmospheric pressure and above 300° C, below which, according to field data, a different mineral assemblage, viz., calcite, quartz and zoisite, would be stable. Fenner (1910) states that in the Watchung basalt when the alteration was delayed until a rather late stage, the nodules of absorbed olivine passed over into chlorite, but in an earlier period, while the temperature was high, garnet was the chief mineral formed. He also points out that with an increase in prehnite, a mineral requiring a lower temperature for formation, in the rocks there is a decrease in garnet. This, too, has been noted in the King Island lavas as mentioned before. Apparently as the temperature fell below the range in which hydrogrossular was stable the excess lime and alumina were absorbed in the formation of prehnite, epidote, and other low temperature hydrothermal lime bearing minerals. The absence of zeolities and the relatively small amount of calcite and quartz for such an altered series are also indicative that the temperature conditions were higher than usual. In support of the late magmatic stage of alteration there is an apparent correlation of the amount of garnet with the degree of crystallization and hence fall in temperature. The fine grained porphyritic rocks such as the aa or fine grained phase of the pahoehoe lavas, which no doubt cooled rather rapidly, contain more hydrogarnet than the coarser grained pahoehoe and spilitic types which contain abundant prehnite.

The general conclusion to be drawn from the hydrothermal study is that if one considers all or some of the albite to be secondary, then both late magmatic reactions and reactions with solutions from external sources have played a part, the former as indicated by the spilitic reaction and the latter by the introduction of alumina. Lime and magnesia, which also play big parts, could have been derived from outside or from the magma itself during the late stage reactions. However, if one considers all the albite to be primary, then most of the alteration is post magmatic and probably due to the granite intrusion.

THE PROBLEM OF THE PYROXENE AND ITS BEARING ON THE ORIGIN OF THE ALBITE

An interesting feature of these lavas is the freshness of the pyroxene when the felspar has been albitized. Usually in spilitic rocks the ferromagnesian minerals are changed to chlorite and epidote but apparently not in this case.

Benson (1915) describes spilitic rocks, in which the augite is unusually fresh, from the Nundle District, New South Wales. He concludes that the albite may be primary in those particular rocks. In the King Island series under consideration there is further strong evidence to support the theory that the albite, or at least some of it, is primary because of its intergrowth and ophitic relation with the augite. The presence of ophitic fabric does indicate on the one hand that the albite may be primary, or on the other hand that it may be secondary, the result of sodic metasomation of normal basaltic rocks as indicated by Turner (1948) when discussing albite associated ophitically with fresh augite from rocks described by Benson from New South Wales and also by Eskola (1925) from Kendjarvi, Finland. However, in this suite the author feels that she can afford to be more assured and state that at least some of the albite is primary because of the eutectic between it and the diopsidic augite. The diagram by Bowen (1928) showing the crystallization of mixtures in the plagioclase field of the system albite-anorthite-diopside indicates that a eutectic does exist between diopside and albite, given the requisite conditions for formation. Although Bowen was concerned with an anhydrous melt and the melt from which this rock was derived was no doubt hydrous it is unlikely that the relationship between albite and diopside would be appreciably affected.

It may happen that some of the albite is primary and crystallized out at an early stage and some late magmatic. Given the suitable conditions of composition of a sodic magma and the right temperature it is possible for the albite to be primary as shown by the eutectic. On the other hand, if temperature conditions are not suitable the magma may crystallize in the same fashion as a normal basaltic magma, leaving at the end a highly sodic fraction which would react with the more basic plagioclase, such as labradorite, to form albite.

Further confusion is added by the presence of beautifully fresh volcanic glass which seems to be too deficient in soda to indicate an original sodic magma from which primary albite could crystallize in spite of its position on Fig. 2, which indicates spilitic affinities.

Resistance of the pyroxene to alteration may be due to the fact that it was already in equilibrium with the surrounding mineral assemblage. Its optical properties determine it to be a diopsidic variety, therefore rich in lime and magnesia and possibly immune to further change by an infiltration of these constituents.

A NOTE ON THE FORMATIONS OF THE LAVAS IN THE FIELD

Brief descriptions of the modes of occurrence of the volcanic series have been given earlier in the paper. The modes of occurrence, with the exception of the pillow lavas, suggest emission under subaerial conditions, the aa and pahoehoe forms and the columnar structure in one of the massive flows being the strong supporting factors.

No definite boundaries can be drawn between the pahoehoe, pillow and aa lavas as there are to be seen transitions from one to the other. In places the lavas are definitely of the pahoehoe, pillow or aa form but in others the pahoehoe seems to merge into the pillow and the aa lava appears to have formed by the breaking up, as it were, of the pillow and pahoehoe lavas. Sometimes the pillow-like structure has taken on a long twisted snake-like appearance about 18 inches in diameter, still with the cavity in the centre. The pahoehoe form appears at times to curl round and resemble the pillow form. Isolated pillows amongst block lava have a fractured appearance indicating that the blocks may possibly have been derived from pillows. This is illustrated by Fig. 1 on Plate II. These pillows often show excellent examples of bulbous budding. Noe Nygaard (1940) refers to floating basalt globes (30-60 cms. in diameter) amongst breccia which are now broken and occur as sector-like fragments or segments but these are the result of a stage during the subglacial intrusion of a magma.

The massive lava flows, on the other hand, are independent and are separated by beds of volcanic tuff and breccia. Breccia tuff and block lava appear between the pillows or interbedded with them. The so-called block lava in this case may be more in the nature of volcanic bombs. At times some of the pahoehoe forms seem to curl around small patches of breccia.

According to Washington (1923) aa and pahoehoe are the chief and most commonly occurring types of basaltic lavas and chemically there is no general difference in the composition of the two forms of lava. Both occur side by side and in the same flow in the Hawaiian Islands. Unfortunately, a chemical analysis of a pahoehoe lava was not attempted because of its amydaloidal nature and the zonal arrangement of crystallization. It would have been interesting to have seen the relationship between FeO and Fe_2O_3 for according to Washington the proportion of FeO to Fe_2O_3 is uniformly higher in the pahoehoe form than in the aa.

The aa form is supposed to be uniformly more crystalline than the pahoehoe which is highly vitreous. However, in the King Island rocks the reverse is the case. The aa lava has given rise to a very fine grained rock, some of which was probably glassy, containing phenocrysts which were originally olivine. Vesicles are wanting. The rock resulting from the pahoehoe lava, on the other hand, is very crystalline, the degree of crystallinity increasing from the surface towards the centre. The pahoehoe rock, mineralogically, seems to bridge the gap between the picrite basalt (aa lava) and the spilite (pillow lava). The pillow lavas sometimes resembles more the picrite basalt, especially when it is found amongst the block lava, and at other times seems to represent the finely crystalline pahoehoe rock. From observation in the field the author is inclined to think that the pillow lavas, generally, are varieties of the pahoehoe lavas and have formed under slightly different conditions of cooling. Possibly the pahoehoe lava has flowed into a local body of fairly shallow water thus facilitating a more rapid cooling and chilling process resulting in the formation of the pillows. As the pillows accumulated to the depths of the water the lava took on again the pahoehoe form.

According to Washington (1923) Day and Shepherd regard the pahoehoe lava as the high temperature form containing much gas and cooling quickly throughout because of the rapid expansion and elimination of the gas.

Although the vulcanicity was closely associated with glacial conditions the extrusions were probably not of the subglacial type as described by Noe Nygaard in 1940, these subaerial lavas having been emitted during an ice recession. There is evidence to show that volcanic action commenced before glaciation ceased in that flows of lava are found interbedded with varves. Also in other places the lavas are irregularly mixed up with the varves, suggesting that the lava was emitted through unconsolidated sediments.

The presence of glass fragments in the breccia towards the base of the volcanic series is again suggestive of conditions suitable for rapid chilling of the magma. Most probably the molten fragments were hurled into the melting ice, thus becoming rapidly solidified to glass.

Above it was suggested that the pahoehoe lava may have flowed into local bodies of water to form the pillow structures. These local bodies of water may have been melted ice water. Association with the pillows are breccias also containing glass, now devitrified or altered for the most part.

Evidence that the centre of eruption was close at hand is provided by the presence of a bed, about 2 feet thick, of 'shower droplet' rock. This rock is described earlier in the paper and as mentioned it is probably the result of the accumulation of small lapilli of lava which have dropped one on top of the other when almost, though not completely, solidified.

Throughout the period of vulcanicity the outpourings of lava were interrupted at intermittent periods when the type of action became explosive and showers of ash and other fragmental material were ejected.

SUMMARY

The volcanic rocks from south-east King Island provide yet another interesting occurrence of a spilitic suite in which the pyroxene is unusually fresh. This time the magma has solidified in the forms of massive, pahoehoe, aa and pillow lavas together with subsidiary amounts of fragmental rocks.

The most important points to be drawn from the study are as follows:—

1. Chemically the rocks may be grouped into spilites and picrite basalts.

2. The lavas themselves provide evidence in the form of ophitic fabric and intergrowth between albite and diopsidic augite that some at least of the albite is primary. However, it is possible for some of the albite to have been formed at a late magmatic stage from soda rich solutions remaining after the normal crystallization of a soda rich basaltic magma.
3. The fragmental rocks provide much confusion in revealing fragments of beautifully fresh glass which is poor in alkalies but very rich in lime. Nevertheless, it shows spilitic affinities when plotted on the triangular diagram, Na_2O, FeO, MgO of Sundius (1930).
4. This volcanic glass when altered appears to have gone mostly and quite readily to hydrogrossular, a fact which is not surprising when the chemical composition of both are compared.
5. Hydrothermal alteration is prevalent and has most probably been due to both late magmatic and post magmatic solutions, the latter being derived from a nearby granite intrusion.
6. The alteration has enriched the rocks in alumina, lime and magnesia and has produced an interesting assemblage of minerals—hydrogrossular (a new occurrence), albite, chlorite, epidote, prehnite, tremolite, calcite and quartz—indicating fairly high temperature hydrothermal conditions at the time of their formation.
7. The pyroxene, diopsidic augite, is unusually fresh and it has been suggested that it was probably in equilibrium with the surrounding mineral assemblage and therefore immune to further change by an infiltration of lime and magnesia in which it was already enriched.
8. The modes of occurrence of the volcanic rocks indicate that vulcanicity commenced before glacial action has ceased. The emission was subaerial and took place, for the most part, during a recession of the ice.
9. The formation of the breccia containing the glass is possibly due to the chilling action of melted ice water.
10. Transitions from pahoehoe to pillow and aa lavas and vice versa exist and the formation of pillow lavas may be the result of the pahoehoe lava flowing into local bodies of this water.

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To Mr. T. McMahon, of the Photographic Section of the University of Tasmania, the author is most grateful for his help and interest in taking the photomicrographs and arranging the plates in this paper.

LOCALITY INDEX

Locality	Quadrangle	Latitude S	Longitude E
Barrier Creek	....	39°58′	144°08′
City of Melbourne Bay	S.E. King Is. 10	40°00′	144°03′
Conglomerate Creek	....	39°54′	144°08′
Dundas	Zeehan 50	41°53′	145°28′
Fraser River	Sea Elephant 6	39°54′	144°02′
Grassy	S. E. King Is. 10	40°03′	144°04′
Grassy River	S. E. King Is. 10	40°03′	144°04′
King Island	....	39°35′—40°16′	143°50′—145°17′
Montana	Zeehan 50	41°51′	145°17′
Nundle	....	31°27′	151°08′
Yarra Creek	S.E. King Is. 10	40°00′	144°03′
Zeehan	Zeehan 50	41.°53′	145°21′

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DESCRIPTION OF PLATES

PLATE I.

FIG. 1.—A field of pillow lavas just south of City of Melbourne Bay.

FIG. 2.—Pillows of lava separated by banded tuff.

FIG. 3.—A pillow of lava showing the differential weathering of the central and marginal areas. Note how the varioles stand out like marbles.

FIG. 4.—Central portion of a pillow of lava showing even weathering, the varioles being distinguished by their lighter colour.

PLATE II.

FIG. 1.—A pillow of lava, showing bulbous budding, amongst the block lava illustrated in FIG. 2. Note the irreguar cracking of the pillow.

FIG. 2.—A field of block lava south of Barrier Creek.

FIG. 3.—A general view of the thin flows of pahoehoe lava showing the general dip of the volcanics.

FIG. 4.—A near view of an individual pahoehoe lava flow. Note the variolitic structure towards the centre.

PLATE III.

FIG. 1.—Weathered surface of the "shower droplet" rock showing the size and shape of the lapilli.

FIG. 2.—Unweathered surface of the same specimen. Note that some of the lapilli are welded together.

FIG. 3.—A specimen of portion of the surface of a pahoehoe lava flow showing ropy structure.

FIG. 4.—A specimen of breccia containing fragments of volcanic glass showing alteration to hydrogrossular indicated by the white bands. The white patches also indicate hydrogrossular replacement.

PLATE IV.

FIG. 1.—Picrite basalt similar to the specimen analyzed. Olivine phenocrysts are pseudomorphed by almost colourless chlorite which is pierced by needles of tremolite. The groundmass is cryptocrystalline and consists of pyroxene and tremolite. ×56.

FIG. 2.—Pahaehoe lava containing radiating augite and laths of albite which are partly replaced by chlorite and hydrogrossular. Albite is the material in the vesicles. ×56.

FIG. 3.—Spilite (basaltic type) showing laths of albite and intergranular augite. ×56.

FIG. 4.—Spilite (pillow lava type) showing radiating augite and albite with granules of magnetite between the tiny sheafs. Analysed specimen. ×56.

PLATE V.

FIG. 1.—Spilite (analyzed specimen) showing graphic intergrowth (eutectic) between diopsidic augite and albite which has been greatly replaced by sericite. The albite is at extinction. ×56.

FIG. 2.—Spilite showing intergrowth as above. The intergrowth has not developed in any definite crystallographic direction. ×56.

FIG. 3.—Spilite (ophitic type) showing albite laths penetrating diopsidic augite. Albite has been greatly replaced by sericite and is at extinction in this figure. Analysed specimen. ×56.

PLATE VI.

FIG. 1.—Volcanic breccia showing glass fragments replaced by chlorite and hydrogrossular towards the margins. ×56.

FIG. 2.—A large fragment of volcanic glass in breccia showing alteration to hydrogrossular, represented by the dark bands. ×56.

FIG. 3.—Portion of the chilled margin of a pahoehoe lava showing the occurrence of hydrogrossular (small dark spots) in vesicles associated with chlorite and pseudomorphing olivine. ×35.

FIG. 4.—Picrite basalt showing the occurrence of hydrogrossular in a large vescile and as a replacement of olivine and the groundmass where it is indicated by the dark patches. ×35.

The photomicrographs (FIGS. 3 and 4) were taken in the Department of Mineralogy and Petrology, University of Cambridge.

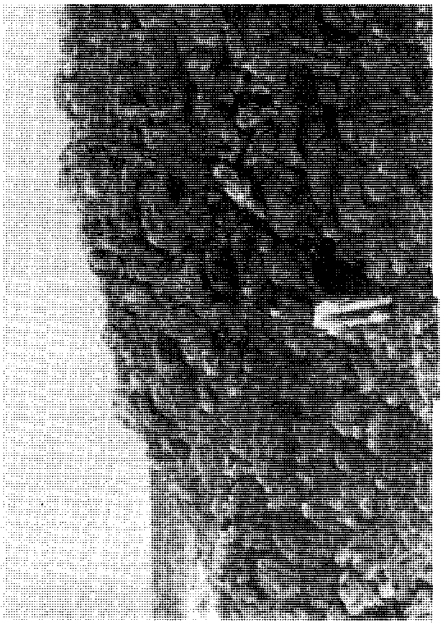

Figure 1

Figure 2

Figure 3

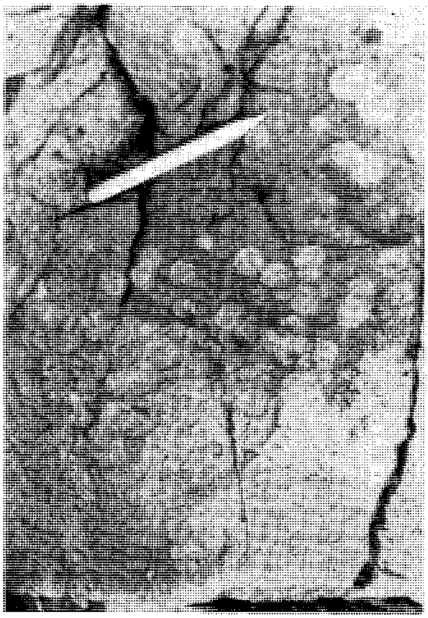

Figure 4

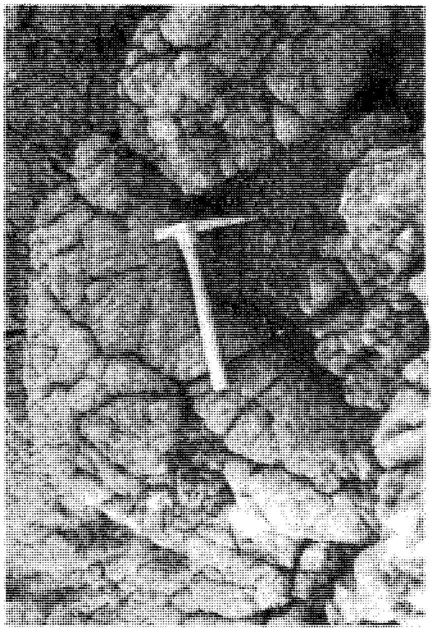

Figure 1

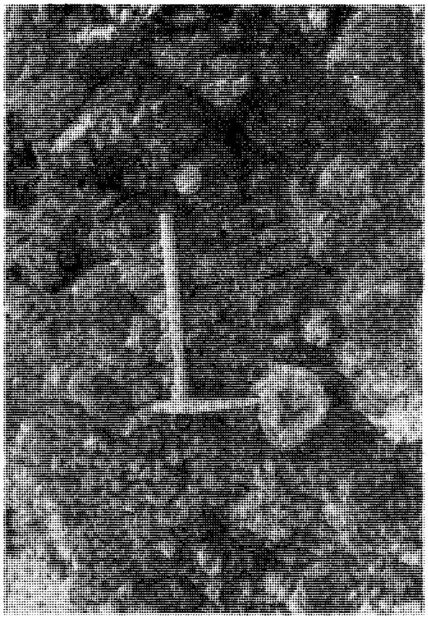

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Figure 3

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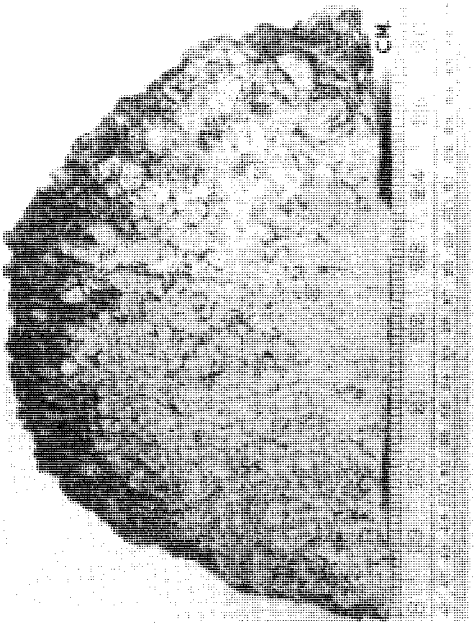

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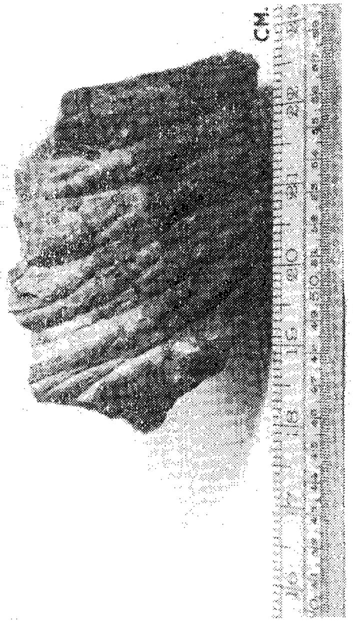

Figure 3

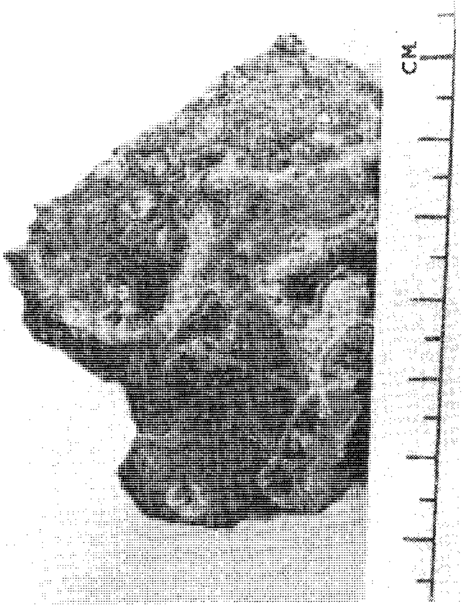

Figure 4

Figure 1 x 56

Figure 2 x 56

Figure 3 x 56

Figure 4 x 56

Figure 1 x 56

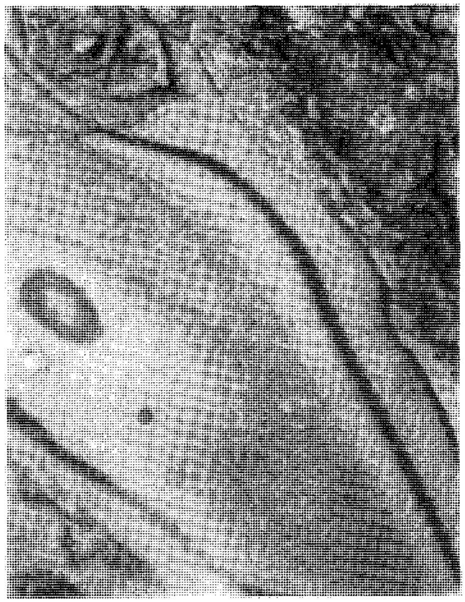

Figure 2 x 56

Figure 3 x 35

Figure 4 x 35

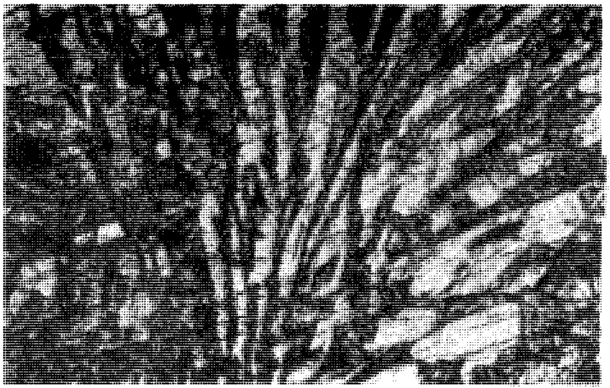

Figure 1
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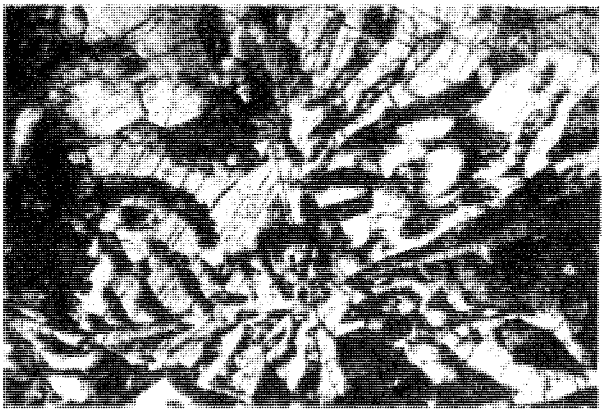

Figure 2
x56

Figure 3
x56