The Nature and Alteration of Some Triassic Sediments From Southland, New Zealand

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Abstract

Triassic greywackes and tuffs have been examined more especially from the northern part of the Taringatura Survey District, where there is a succession approximately 28,000 feet thick. A progressive increase in the degree of albitization of detrital plagioclase towards the base has been recognized and there are concurrent increases in the amounts of secondary lime-bearing minerals. Abundant beds of glassy tuffs were converted during diagenesis to zeolite rocks consisting mainly of heulandite or analcime, and these minerals are still found in the upper parts of the succession. Towards the base analcime is now represented only by pseudomorphs and most masses of devitrified tuffs have been converted to laumontite rock. Metasomatic effects accompany these changes and in extreme cases quartz-albite-adularia-pumpellyite metasomatites are developed. Chemical and spectrographic analyses are presented to show the course of the changes. The metamorphism is low-temperature hydrothermal in its effects although unrelated to igneous activity. It took place progressively with increasing temperature under increasing load and was made possible by vast quantities of water stored in volcanic glass and in zeolites of early formation

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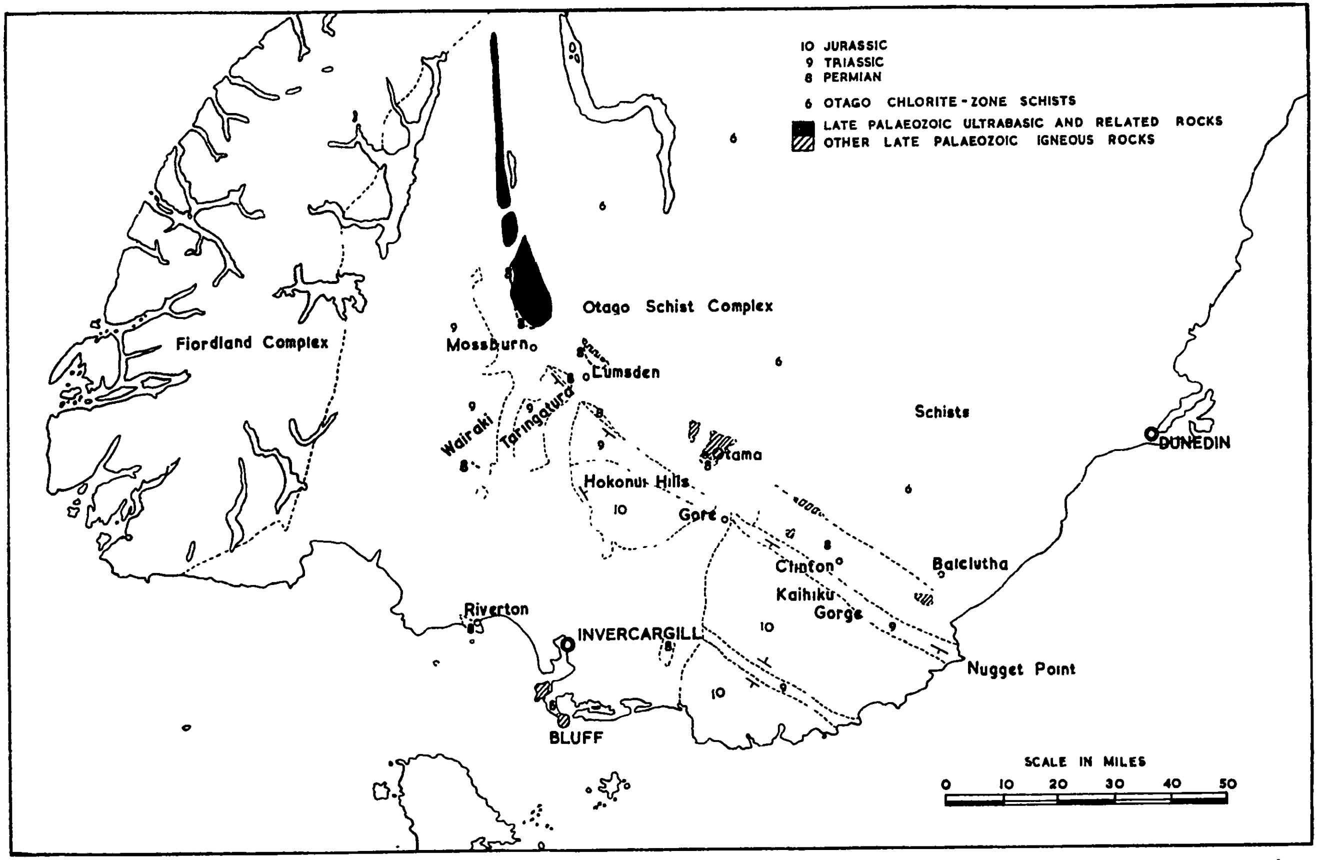


TEXT-FIG. 1.—Locality map of parts of Southland and Otago. The approximate distributions of certain pre-Cretaceous formations are indicated.

INTRODUCTION

In the northern part of the Taringatura Survey District, Southland, New Zealand (locality map, Text-fig. 1), pyroclastic materials make up a noteworthy part of a Triassic greywacke succession about 28,000 feet thick (Coombs, 1950). During the original work on the area it was noticed that thick beds of tuffs and tuffaceous greywackes in the lower part of the section were extensively albitized, and zeolitized beds, including beds of laumontite rock, were found to be widespread. The curious alteration of these tuffs seemed worthy of further investigation. Furthermore, the fact that a very large series of sediments is exposed in section, unaffected by igneous intrusion and undeformed except by a great synclinal fold, affords an opportunity to investigate any correlation between incipient metamorphic effects and age or depth of burial of the sediments. The present study is mainly concerned with these two problems.

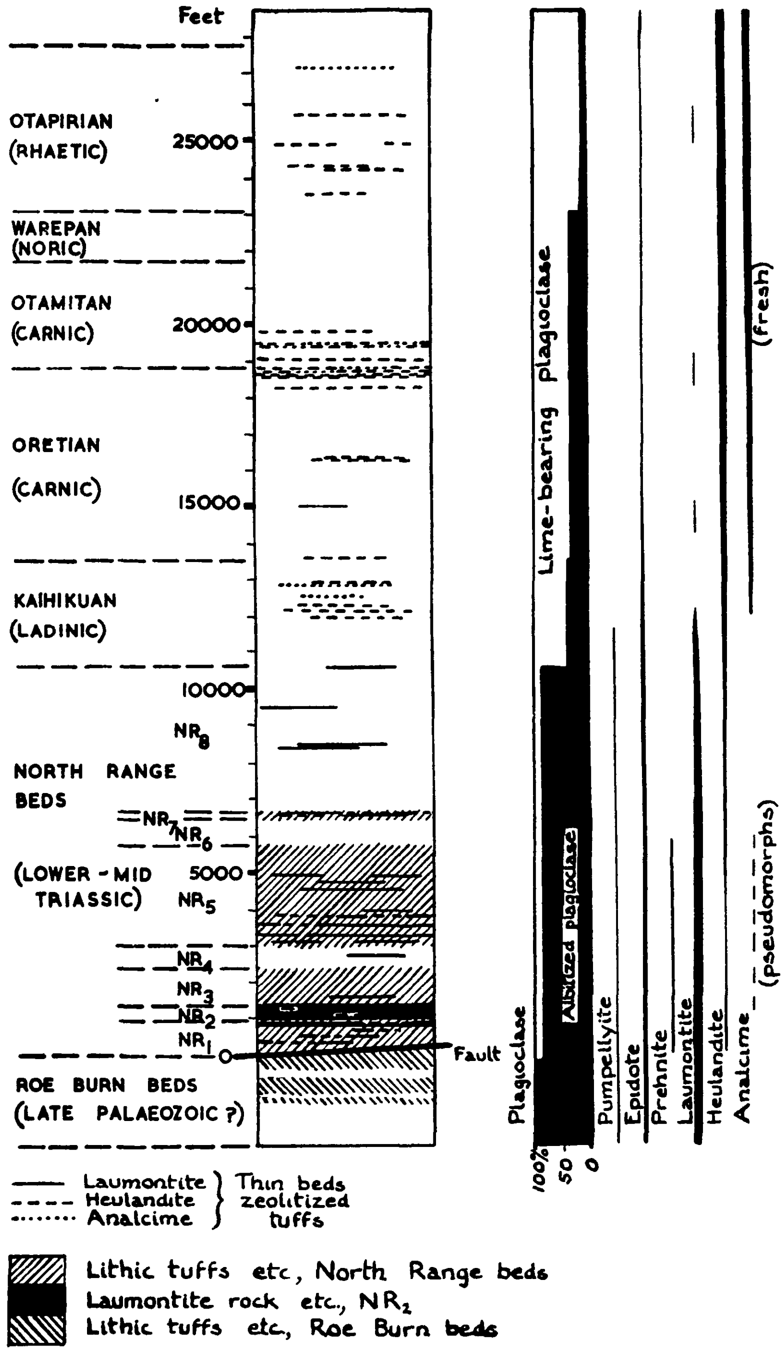
Apart from descriptions of conglomerate pebbles (Mackie, 1935, Watters, 1952) no accounts have been published of Southland Mesozoic petrography. Descriptions of certain Triassic greywackes and semi-schists from the north side of the Otago schist belt have been furnished by Mackie (1936) and Turner in Williamson (1939), while simliar greywackes of less certain age have been described by Amies (1950). The schists themselves (e.g., see Turner, 1938; Hutton, 1940) lie to the north-east of the Southland Mesozoic sediments, being separated from them by a belt of Late Palaeozoic greywackes and subordinate volcanics.

There are several references to ash beds in rocks of Triassic age from western Auckland (e.g., Henderson and Ongley, 1923, pp. 21-23; Henderson and Grange, 1926, p. 36) and in Southland (Cox, 1878; Rout and Willett, 1949, p. 300; Watters, 1952). These occurrences do not appear to be associated with flow rocks, nor have these been found at Taringatura. In Canterbury and the Southern Alps, however, Triassic spilitic pillow lavas and ash beds occur at many localities and are often accompanied by limestones and cherts (McKay, 1881a, 1881b; Speight, 1928, pp. 9–10; Wellman, Grindley and Munden, 1952, p. 218). These Canterbury and North Westland volcanics are in a region mapped by Wellman (1952) as being of his "Alpine Facies". In the corresponding rocks of the North Island, too, there are numerous occurrences of volcanic rocks, some of them possibly being of Triassic age—e.g., basic pillow lavas (Wellman, 1949) and acidic tuffs and rhyolites (Fraser and Adams, 1907, p. 43).

It is clear that Triassic vulcanicity was of great importance in New Zealand. Near Taringatura it was both prolonged and repeated as the present work will show. Several dykes and boss-like bodies of porphyrite intrude Triassic sediments in the Wairaki district (Rout and Willett, 1949; Park, 1921, p. 40) about a dozen miles south-west of Taringatura and they may be connected with a late episode of the same general period of volcanic activity, but with these possible exceptions, the roots of the Southland Triassic volcanoes, which probably lay to the south and west of Taringatura, remain to be recognized, if indeed, they are not submerged beneath the sea.

SUMMARY OF STRATIGRAPHIC AND FIELD RELATIONSHIPS

The structure and stratigraphy of Taringatura have already been described and a map has been presented (Coombs, 1950). A new diagrammatic column



TEXT-FIG. 2.—Mineralogical features in relation to stratigiaphy, Taringatura Survey District, Southland. Known beds of zeolitized tuffs are indicated at the appropriate horizon, though further field work would undoubtedly reveal more. It is not possible to show all beds where several occui close together. The general distribution of various minerals is shown diagrammatically at the right.

(Text-fig. 2) shows the relationship of petrographic features to stratigraphy. The terminology for the Upper Triassic beds is adopted from Marwick (1950) who renamed as stages the "series" of earlier work.

A. *The Roe Burn Beds* (Late Palaeozoic ?)

Dipping beneath the lowest Triassic rocks with faulted contacts is a poorly exposed series of tuffaceous greywackes, pebble bands and siltstones. All members are rather deeply altered. Detrital lime-plagioclase is replaced by laumontite and albite. Igneous pebbles are mainly meta-andesites.

B. *The North Range Beds.* (Plate 1.)

The lowest 10,600 feet of strata conformable with rocks of known Late Middle to Upper Triassic age have been separated (1950) as the North Range beds and are believed to be of Lower to Middle Triassic age. The group was subdivided into eight units, indexed NR_1 to NR_8. Of these, $NR_{4,6,8}$ consist of indurated mudstones with interbedded tuffaceous bands. Of the others, all but NR_2 consist essentially of lithic tuffs (terminology of Wentworth and Williams, 1932) made up of albitized andesitic material, with an admixture of devitrified glass Rare specimens are found that contain unaltered, lime-bearing plagioclase. In some rocks small scattered fragments of quartz and slaty metamorphic rocks are apparent in thin sections. In such cases devitrified glass shards become rare and the crystalline volcanic fragments have a tendency to be crudely rounded. These rocks are better described as tuffaceous greywackes. Numerous beds of altered vitric tuffs several inches to about twelve feet thick, occur among the more massive lithic tuffs. These vitric tuffs are often traceable for several miles and are interesting in the field on account of the intraformational folding they sometimes display, and the highly fragmented plant remains often found in them. They are invariably altered either to a tough, dark-green rock consisting mainly of heulandite, or to a rather earthy-looking, whitish or buff-coloured laumontite rock, which often forms long, prominent outcrops (Plate 1, Fig. 3.) Regular jointing cuts cleanly across the intraformationally-folded zeolitic rocks. It thus post-dates the intraformational folding, and since the joints are not healed they post-date the main period of zeolitization.

Bed NR_2 is a massive bed of water-sorted vitric and crystal-vitric tuffs, 450 feet thick. Most of the ash is altered to laumontite, but some is altered to heulandite. The laumontite rock contains tiny streaks and patches rich in secondary quartz and feldspar, and it also contains many larger masses of metasomatic quartz-feldspar rock, commonly apple-green in colour, occasionally pink or brown. Particularly instructive exposures of these are to be seen at a massive outcrop of laumontitized tuff on the north summit ridge of the North Range, grid reference Prov. 1 ml. Series S.159/310821. The point described is about 1000 yards north-west along the ridge from the Castlerock—Castle Downs roadline, the North Range section of which has recently been metalled to provide access to a new limeworks at the North Range limestone outlier. On the steeply inclined dip slope of the crag, numbers of metasomatic bodies are to be seen. They approximate in form to oblate spheroids with their longest dimensions parallel to the bedding planes, though they in no way disturb the bedding, being superimposed on the sedimentary structures. Dimensions of some measured bodies ranged from 1 foot to 4 feet maximum diameter, by 7½ inches to 18 inches in depth. Roughly concentric veinlets appear in the laumontitic country rock about 2 inches from the periphery of a typical example 22 inches in diameter. The outer zone of the metasomatite body itself has numerous concentric veinlet-like sheets about 1 to 4 mm. thick, and a little residual laumontite in the outermost 2 inches. The inner core, 13 inches in diameter, is free of megascopic veining. The concentric veinlets are feldspathic and weathering proceeds differentially along them (Plate 1, Fig. 2) eventually causing the quartz-feldspar aggregates to drop out of the country rock leaving a rounded hollow.

For convenience of reference the altered vitric tuffs of bed NR_2 may be classified as follows:—

Type I Glass replaced by minutely fibro-lamellar heulandite. Clastic feldspar mostly clear unaltered andesine.

Type II Glass replaced by laumontite. Plagioclase uniformly albitized.

Type III Non-zeolitic metasomatites consisting of quartz, albite and adularia, with or without pumpellyite. All gradations occur between:

Type IIIa—essentially quartz-albite rocks and

Type IIIb—essentially quartz-adularia rocks.

Bed NR_3 contains bands of conglomerate in which the pebbles are generally less than two inches in diameter and moderately rounded. One pebble was found in which alteration of plagioclase was incomplete, but all the others examined have been albitized and show structures and minerals identical with those of the larger fragments in the lithic tuffs. There can be little doubt that they are products of the same volcanic activity as the tuffs. The same conglomerate beds may be traced into the Hokonui Hills. Pebbles collected there by Mr. I. C. McKellar and given to the writer yield important information concerning the former nature of the Taringatura rocks, because at the Hokonui locality alteration is much less complete and feldspars and pyroxenes are commonly fresh. Types ranging from feldspar basalt to leucocratic andesite were noted, with normal augite andesites predominating.

C. *Upper Triassic Rocks*

The presence of many bands containing marine fossils has allowed the subdivision of the long Late Middle and Upper Triassic sequence into groups correlated with the well known stages of the New Zealand Triassic. The Kaihikuan Stage at Taringatura is taken to commence with a conglomerate marking the first influx of granitic and quartz-dioritic debris, which is completely lacking in the North Range rocks. In all succeeding beds, quartz, biotite and potash feldspar. rare in the North Range, are almost constantly present as detrital minerals and muscovite is occasionally found. Augite becomes much rarer than before, but plagioclase remains the chief constituent of almost all coarser-grained sediments. Fragments of aphanitic, intermediate to acidic, volcanic rocks are ubiquitous and there are many tuff bands, those so far recognized being shown in the petrographic-stratigraphic column (Text-fig. 2). Andesite tuffs are rare, rhyolites are probably not uncommon, and dacites or rhyodacites occur at many horizons.

Non-pyroclastic sediments include conglomerates, arkoses, greywackes and indurated mudstones and siltstones, all generally lighter in colour than the dull bluish-grey rocks of the North Range. The coarse grain size, the highly feldspathic nature of the sediments and the presence of many conglomerate bands show that considerable relief was maintained more or less continuously throughout the period and that erosion was rapid. Certain non-fossiliferous feldspathic sandstones show colour mottling in blue, pink or yellow. Some beds contain angular mud pellets. The greywackes often show graded bedding, but current bedding and ripple marks have not been seen.

MINERALOGY

The occurrence and significance of the following minerals will be dealt with in turn.

- Quartz
- Plagioclase
- Potash feldspar
- Laumontite
- Heulandite
- Analcime
- Stilbite
- Pumpellyite
- Prehnite, Epidote, Calcite
- Sphene
- Celadonite
- Chlorite
- Clay minerals (kaolinite and montmorillonite-nontronite)
- Pyrite
- Augite
- Accessory detrital minerals

QUARTZ

Secondary quartz is an important constituent of the quartz-albite-adularia metasomatites, but apart from tiny vein-like films in the metasomatites, only one specimen of vein quartz—a surface pebble associated with the NR_2 tuff bed—was found in the Taringatura area. Tiny crystals of secondary quartz are widespread in the laumontitized tuffs. They tend to be euhedral, projecting into laumontite from the edges of devitrified shards and they may eventually coalesce into a granular mosaic (Plate 2, Fig. 1).

PLAGIOCLASE

a. *Occurrences in the North Range beds*

Rare "islands" in the North Range lithic tuffs contain clear fresh plagioclase ranging in composition from An_{32} to An_{50} (8871)* and similar plagioclases are found in the associated heulanditized tuffs—e.g., An_{36} to An_{51} (8768) and An_{29} to An_{38} (8767). Determinations by the Federow method indicated high-temperature optics as described by van der Kaaden (1951) and others. In addition these rocks contain a proportion of inclusion-studded grains of albite and oligoclase, some of which may have been altered in place, and some of which have probably been derived from older, altered rocks. In the vast majority of North Range rocks phenocrystic plagioclase is uniformly low-albite, composition An_{0-4}. Such grains are always faintly clouded and contain scattered flecks of sericite (cf. Bailey and Grabham, 1909, p 254). Occasionally there are inclusions of calcite, pumpellyite, epidote, laumontite or prehnite and there can be no doubt that such albite owes its uniform, lime-free composition to albitization of andesine such as is preserved in the "islands" just described

* Four-figure numerals are the catalogue numbers of specimens in the collection of the University of Otago.

Purely secondary albite appears as groups of small crystals in certain of the laumontitized tuffs, and in the Type IIIa metasomatites it is a principal constituent. Here it occurs as a felt of stout, tabular crystals up to 0·3 mm. long showing close-set albite twinning. Universal stage determinations indicated compositions An_{0-2} corresponding exactly with albitized crystal fragments in the same rocks, from which the new albite differs in the complete absence of sericite inclusions and in its less clouded nature.

b. *Albitization of Upper Triassic detrital plagioclase*

Detrital plagioclase crystals in the Upper Triassic rocks are sometimes albitized, and sometimes quite fresh, or again they may be partially converted to albite, more especially in the neighbourhood of cracks and cleavages. A statistical survey of Taringatura thin sections is instructive. (Table I.)

TABLE I.

Albitization in rocks from Taringatura (northern section)

Stage	Stratigraphic Height.	Number of Rocks Examined in Thin Section.	Percentage of Slides With Plagioclase Entirely Albite.
Otapirian	27,700–23,000ft.	10	10%
Oretian, Otamitan, Warepan	23,000–13,500ft.	36	33%
Kaihikuan	13,500–10,600ft.	24	38%
North Range beds	10,600ft–base	105	85%
Roe Burn beds	——	20	100%

This count does not give a quantitative estimate of albitization in the respective formations. Too much weight is given to certain particularly interesting types which have been much sectioned, such as the heulandite-andesine-bearing tuffs of the North Range beds, and no account is taken of grain size. The Upper Triassic rocks of the northern part of the Taringatura Survey District are continued to the south in an area being described by Mr. J. D. Campbell. Through his friendly interest it has been possible to examine 117 thin sections from this southern region. Of 103 slides from the Oretian-Warepan-Otamitan stages 32% had detrital plagioclase entirely albitized, and of 14 Otapirian, unfortunately mostly of the finer grain sizes, only one did not retain lime-bearing plagioclase. These figures agree closely with the corresponding data in Table I. In order to make the analysis as non-selective as possible, figures are given for all slides which have been cut, irrespective of grain size. A strong tendency is suggested for increasing albitization towards the base of the section with perhaps a relatively rapid change between the North Range beds and the Kaihikuan, coinciding with the change in the dominant type of sedimentary and volcanic debris. It should be noted that minor reversals would appear if the stratigraphic units were too finely subdivided, especially if a disproportionate number of coarse- or fine-grained rocks were placed in one subdivision. The coarse-grained sediments were distinctly more prone to alteration than the fine. Thus of 73 slides from the southern region roughly estimated by inspection to be of siltstone or finer grades (many of them fine vitric tuffs) only 15% had more or less completely albitized plagioclase, whereas of 44 slides of coarser-grained rocks, 52% were albitized.

c. *Feldspar authigenesis in Upper Triassic sediments*

Quite distinct from the albitization of detrital plagioclase is the formation of authigenic albite in Upper Triassic rocks especially in the coarser-grained sediments. The new albite (composition An_{0-4}) is found as water-clear overgrowths on detrital plagioclase grains largely in optical continuity with the host if the latter has been albitized, but frequently showing a finer twinning pattern. More voluminous are clusters of elongated grains 0 05–0 3 mm. long which are found in the spaces between sand grains. They show albite twinning.

A review of the literature up till 1933 dealing with authigenic feldspars in sediments was given by Boswell and important later records and discussions have been contributed by Tester and Atwater (1934), Crowley (1939), Honess and Jeffries (1940). Some writers have suggested that formation is more or less contemporaneous with deposition, but Reynolds (1929) and Heald (1950) both give evidence that in the rocks which they describe, formation post-dates consolidation of the sediments In view of the fact that interstitial authigenic albite is undisturbed, whereas surrounding grains of detrital plagioclase have sometimes been fractured and flakes of biotite distorted during compaction, there can be little doubt that this is true in Taringatura also.

Gruner and Thiel (1937) found that an Ordovician shale which had not, apparently, been subjected to particularly deep burial or to the action of volcanic emanations, consisted of about 66% potash feldspar. They concluded that its formation was probably due to abstraction of potassium by clayey material and alteration to orthoclase, a reaction shown to be possible by Gruner's low-temperature synthesis of orthoclase from montmorillonite (1936). The authigenic adularia found in small amount in some Upper Triassic rocks from Taringatura may have a similar explanation. The authigenic albite remains to be explained. Hatch, Rastall and Black (1938, pp. 291–292) suggested that authigenic feldspar in limestones may be related to the presence of volcanic ash, and Honess and Jeffries (1940) have indicated that the alteration may proceed through a zeolitic stage. It will be shown later that this process has been operative in the Taringatura tuffaceous greywackes, authigenic albite often being intimately associated with residual analcime which had earlier formed at the expense of glass (e.g., 9048).

POTASH FELDSPAR

a *Adularia in the North Range*

Adularia of extremely small grain size is locally a very important secondary mineral in the North Range It occurs in the quartz-albite-adularia metasomatites:

(i) In close-set concentric veinlet-like films a millimetre or less thick as in 8819;

(ii) As minute rhomb-shaped or irregular crystals 0 01–0·02 mm. diameter, disseminated through the rock as in 8817;

(iii) As rich concentrations of tiny granules in devitrified shards as in 8818, and also in some of the heulanditized tuffs;

(iv) With or without albite and kaolinite in pseudomorphs after analcime as in 8824, 8828, The determination is based on chemical analyses of adularia-rich rocks, 8817, 8819; on staining tests with sodium cobaltinitrite on polished surfaces etched with hydrofluoric acid; on concordant refractive indices and on a confirmatory X-ray powder photograph of veinlet material from 8819. In this rock (8819), the refractive index α of the mineral is $1{\cdot}518 \pm$ 003, and in pseudomorphs after analcime in 8824, $\alpha = 1{\cdot}518$, $\gamma = 1{\cdot}524 \pm {\cdot}003$. Spectrographic analyses discussed later show that the North Range adularia carries appreciable barium and rubidium.

b. *Potash feldspar in Upper Triassic sediments*

Authigenic adularia has been observed in a number of Upper Triassic tuffs and greywackes, a good example being a Kaihikuan rhyolite crystal tuff, 8974, in which narrow overgrowths of water-clear adularia partially surround cloudy crystal fragments of perthite and pass outwards into discrete rhomb-shaped crystals in a matrix of recrystallized quartz, albite and adularia. The refractive index γ of this adularia is $1{\cdot}524 \pm {\cdot}003$. Detrital potash feldspar is very rare in the North Range beds and is rarely abundant in the Upper Triassic rocks, but in the same crystal tuff, 8974, rather irregularly perthitic grains occur closely packed with quartz which is often embayed by devitrified groundmass material. An aggregate extinction angle $\alpha' \wedge a$ on (010) $= 13°$ indicates a bulk composition in the orthoclase cryptoperthite series of about $Or_{45}Ab_{55}$ according to Tuttle (1952, fig. 3). The optic axial angle of the potash phase is variable between 50 and 70°, apparently depending on the extent to which exsolved albite has been cleared from the part of the crystal observed. The plagioclase phase is a fairly pure low-albite. Segregation of the exsolved phases has probably proceeded during the post-depositional alteration of the sediments.

LAUMONTITE

The presence of laumontitized vitric tuffs has been mentioned above and an account of the mineralogy and origin of laumontite in Southland has already been published elsewhere (Coombs, 1952). The Taringatura occurrences may be summarized as follows:—

(i) Laumontite is the most important alteration product after glass in the North Range vitric tuffs, and extensive beds of impure laumontite rock are found. The laumontite was formed after heulandite and analcime, but before the Type III metasomatites.

(ii) In many Southland greywackes laumontite is a joint replacement product with albite of lime-bearing plagioclase. Directly or indirectly, the breakdown of lime-bearing plagioclase is a main feature in the origin of most laumontite.

(iii) It occurs in small amount as a cement in one or two upper Triassic sediments.

(iv) Several specimens of Otapirian lamellibranchs have recently been observed in coarse arkosic matrix in which the shell material has been replaced by laumontite.

HEULANDITE

a. *Occurrence and optical properties*

A zeolite occurring as a fibro-lamellar replacement product of glass proved difficult to identify on account of its extremely fine grain size, the fibres rarely reaching a length of 0 02 mm. On casual inspection it could easily be mistaken for glass as has probably occasionally happened. On the basis of X-ray powder photographs and concordant optical and chemical data the material has been proved to be heulandite.

In contrast to the occurrence of laumontite in Taringatura, heulandite is found with unaltered plagioclase fragments and occurs throughout the succession reaching its maximum development in the upper parts of the column. In the North Range beds it is found only in discontinuous patches, more especially in fine-grained vitric tuffs. Fibrous tufts of the mineral radiate inwards from the edges of devitrified shards and may occupy the whole width of the narrower ones or meet in a central suture which is sometimes marked by a chloritic film. The aggregates are often clouded with finely-divided red dusty iron oxides precipitated during the change from volcanic glass to zeolite. Zeolitized shards are always surrounded by iron- and magnesium-rich films of celadonite, chlorite, or montmorillonite-nontronite clay minerals, which preserve and emphasize the characteristic outlines of ash particles. In examples from the North Range the "chloritic" films are sufficient to colour the rock a deep bluish green, but the generally more acid tuffs of the Upper Triassic are lighter in colour and often salmon-pink due to the iron oxides included in the heulandite. This is well shown in a number of beds near the top of the Oretian. The zeolite replacing glass in Upper Triassic tuffs is even more poorly crystalline than in the North Range, but it still gives the main lines of the heulandite X-ray powder pattern and must be closely related. All these examples are compact, thoroughly cemented and surprisingly hard rocks. Corresponding types are found far outside the Taringatura area. Thus salmon-pink zeolite tuffs of the same age have been observed in collections from the Mount Hamilton area a dozen miles to the north-west and dark-green heulanditized tuffs of North Range age continue far into the Hokonui Hills to the south-east. Similar alteration has been observed by the writer in tuffs which accompany Late Palaeozoic greywackes immediately south of the Otama igneous complex.

The only optical properties determinable in the typical development of the mineral are a negative sign of elongation and a refractive index 1·499 ± 002 along the length of the fibres. The birefringence is weak. Rarely, better formed crystals occur in vesicles within the larger glass shards or in interstices. Thus in a crystal tuff, 8991, from the Kaihikuan, authigenic heulandite crystals 0 1 mm. long, line the walls of small cavities about 0 5 mm. across The crystals are in the form of tablets flattened parallel to the (010) cleavage and show combinations of pinacoid and dome faces. The optic axial plane is perpendicular to (010), (+) 2V small, extinction angle $\alpha \wedge c = 4$–$5°$. Within the ring of heulandite crystals, the cavities are filled with quartz and some chlorite of later deposition than the heulandite. Prisms of apatite are also present.

b. *Analysis*

Due to the extremely fine grain size and the intimate association with celadonite and chloritic minerals, separation of a pure sample for analysis was not achieved. A portion of one of the two analysed heulandite-bearing tuffs from the North Range (8768, Table VIII) was crushed to pass 300-mesh sieves and repeatedly centrifuged to obtain a fraction of specific gravity less than 2·29. A chemical analysis was carried out on a small amount of material; the result is given in Table II together with analyses of a normal heulandite and of the variety "clinoptilolite" for comparison. The summation of the analysis is unsatisfactory, but it is included to give an approximate basis for discussions on the origin of the mineral, and to show that the Taringatura material is essentially a normal heulandite and not the silica-rich variety clinoptilolite (Schaller, 1923, 1932) which has frequently been reported in tuffs. The structural formula calculated from the analysis is:

$$(Na_{0.5}\ K_{1.6}\ Ca_{3.4})\ (Al_{8.8}\ Si_{27.2})\ O_{72}.\ 22{\cdot}1\ H_2O.$$

This accords reasonably well with the general formula proposed by Hey and Bannister (1934), namely,

$$(Na, K)_x\ Ca_y\ Al_{(x+2y)}\ Si_{36-(x+2y)}\ O_{72}.\ 24\ H_2O$$

where $x + y = 4$ to 6, and $x + 2y = 8$ to 10 in most heulandites, but drops as low as 6 in clinoptilolite.

Spectrographic analysis of the rock showed 5,000 parts per million of strontium, or 0·60% SrO. The heulandite probably contains about 1% SrO listed in Table II as CaO. High strontium appears to be a common feature of heulandites. Thus Slawson (1925) reports 0·59% SrO in the Berufjord mineral (column B) and Walker and Parsons (1922) recorded two heulandites from Nova Scotia with 0·48% and 1·26% SrO respectively.

TABLE II.

Analyses of heulandite and clinoptilolite.

	A	*B*	*C*	*D*
SiO_2	58.6	58.55	64.30	66.40
Al_2O_3	16.0	17.64	12.78	11.17
Fe_2O_3 (total Fe)	1.8	—	0.82	0.57
MgO	1.3	—	0.62	0.17
CaO }	6.7	5.82	2.42	1.94
SrO }		0.59	—	—
Na_2O	0.6	1.25	3.96	2.27
K_2O	2.7	0.81	1.36	3.58
H_2O+	11.6	15.88	9.50	13.31
H_2O-	2.7		4.78	
	102.0	100.54	100.54	99.41
Sp. Gr.	2.24±.03	—	—	2.15±.03
Optical properties:				
α	—	1.4991	—	1.476
β	1.499	1.5008	1.480	—
γ	—	1.5002	—	1.479
γ — α	small	.0061	small	.003

References:

A. Impure heulandite from tuff 8768, North Range, Taringatura S.D., New Zealand.

B. Heulandite from Berufjord, Iceland (C. B. Slawson, 1925).

C. Clinoptilolite from altered tuffs, Dome, Arizona (Bramlette and Posnjak, 1933). J. G. Fairchild, analyst.

D. Clinoptilolite ("mordenite") from Hoodoo Mtns, Wyoming. (Pirsson, 1890.) L. V. Pirsson, analyst.

c. *Significance of heulandite in tuffs*

Bramlette and Posnjak (1933) found that "clinoptilolite" is associated with montmorillonite as an important alteration product of acid pyroclastics in the Miocene Monterey group of California. They also found it as relict, almost isotropic shards in bentonites from Dome, Arizona (Table II, analysis C), and in a bentonite derived from a more calcic glass from Pedro, Wyoming, associated with phenocrysts of andesine-labradorite and biotite. They considered that clinoptilolite is an intermediate product in the alteration of volcanic glass to bentonite clay minerals, and they point out that it is of rather similar chemical composiion to the parent glass.

Kerr and Cameron (1936) later detected clinoptilolite in a bentonite from Tehachapi, California, and Fenner (1936, p. 247) found it to occur as a cement and groundmass replacement in a borehole at the Upper Geyser Basin, Yellowstone, where it is confined to a depth range of 62 to 86 feet corresponding to a present-day temperature of approximately 125°C. More recently Gilbert and McAndrews (1948) have described authigenic clinoptilolitic heulandite in sandstone from Santa Cruz County, California, associated with, though not directly replacing fragments of volcanic glass, and Steiner (1953) has found heulandite together with ptilolite and analcime in boreholes at Wairakei in the New Zealand thermal region.

It is clear that clinoptilolite, a mineral which has a composition not unlike a rather acid glass enriched in water, is to be recognized as an important low-temperature alteration product after such glass, especially in fragmental rocks. Hot-spring activity has certainly facilitated the change in the Yellowstone example and at Wairakei, but in the other cases cited does not appear from the published descriptions to have been active. In these, as is believed to be the case with bentonite (Ross and Hendricks, 1945), alteration was probably achieved in the presence of groundwaters only, or perhaps sea or lake waters. Ross and Hendricks consider that a pre-requisite for the formation of bentonites is the availability of bases such as Mg'', and that K' must be leached away. Removal of K', however, is not so marked during heulanditization. In fact the formation of celadonite and possibly adularia in the Taringatura heulandite rocks shows that the concentration of potassium was great enough for formation of new potassium-bearing minerals, and bentonites were not produced.

Heulandite has a lower content of silica and alkalies and higher lime and alumina than clinoptilolite, and so its formation would require either a more basic parent material, or greater changes in composition during alteration. Both factors may have influenced its formation in the North Range tuffs. The associated phenocrysts, andesine, augite and rare hornblende indicate that the glass in these rocks was distinctly more basic than in most of the above American occurrences, but even so a considerable loss of soda must have occurred to produce a heulandite with 2·68% K_2O and only 0·56% Na_2O. The Upper Triassic tuffs were distinctly more acid than those of the North Range, but nevertheless the refractive index of the heulandite to which their glass has altered remains close to 1·50. Formation of heulandite from an acid glass would require the separation of silica, and it is significant that a powder photograph of a heulandite-rich fraction separated from the Oretian tuff 8012 shows that quartz is present. Quartz and heulandite here constitute joint cryptocrystalline alteration products of the glass.

ANALCIME

a *Occurrence*

The distribution of analcime is interesting and significant. In the North Range beds it has not been found, but a number of veinlets 1–3 mm. thick in the quartz-albite-adularia metasomatized tuffs are packed with perfect icositetrahedral pseudomorphs of albite and/or adularia set in a base of quartz (Plate 2, Fig. 3). Sometimes very cloudy icositetrahedra occur in the groundmass as well. Icositetrahedral pseudomorphs of laumontite with subordinate quartz after analcime occur in the laumontite rock, 8784.

The lowest observed occurrence of analcime, as distinct from pseudomorphs, is about 2,000 feet above the base of the Kaihikuan, and 300 feet higher it occurs rather freely as a replacement product in a fine devitrified rhyodacite tuff. In beds of the Oretian and Otamitan Stages analcime is a locally abundant, though inconstant constituent of tuffaceous rocks, and it continues at various horizons to the top of the section. It replaces glass and fills interstices. For example in 9048, a tuffaceous arkose, a few icositetrahedra 0 1–0 5 mm. diameter are discernible in the thin section. They are surrounded by secondary quartz and albite and are themselves embayed by these minerals. A concentrate was separated by crushing and centrifuging and an X-ray powder photograph showed the characteristic analcime pattern with fainter quartz lines in addition. The refractive index was 1 483 ± ·002.

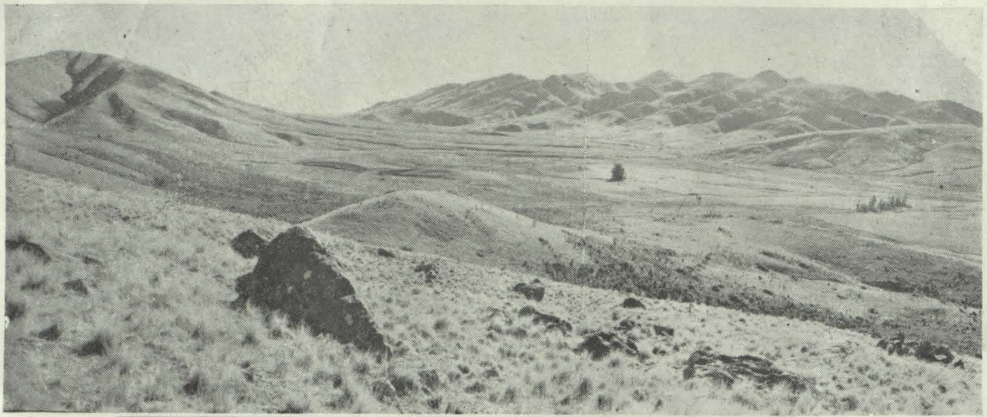
Analcime is evidently widespread in tuffaceous Triassic greywackes of the South Island. It has been collected by the writer from near Nugget Point (9097) and from Kaihiku Gorge (9108). It is also present in Oretian sediments collected by officers of the New Zealand Geological Survey near Nelson, where Triassic greywackes occur of similar facies to those of Southland.

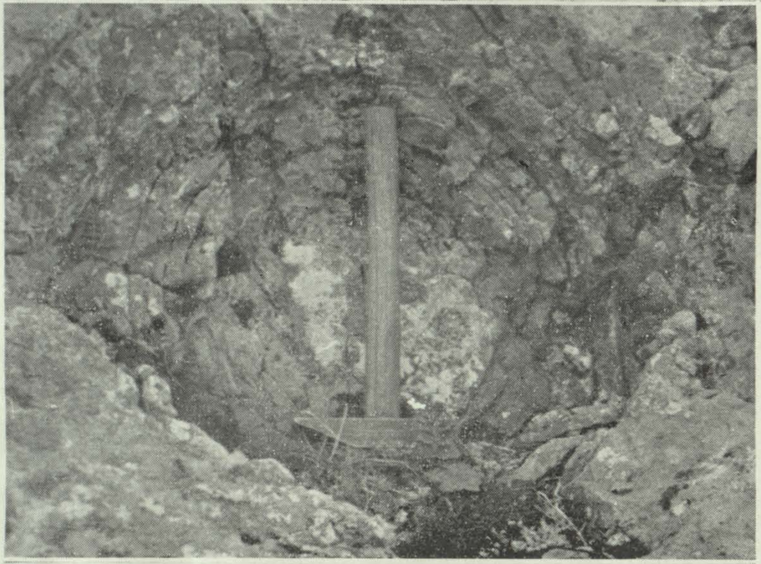
b. *Significance*

Authigenic analcime has often been reported in pyroclastic rocks. Thus Tyrrell and Peacock (1926) describe an Icelandic occurrence of analcime which is associated with faujasite, a potassium analogue of analcime. and limonitic or chloritic material together representing joint alteration products of palagonite tuff.

In the Great Geyser Basin bore-hole of Yellowstone described by Fenner (1936), analcime occurs with quartz and adularia in dacitic gravels and sands altered by alkaline, hot-spring activity in the depth range 86 to 216 feet. This corresponds with a present-day temperature of 125–157° C. and is just below the zone in which heulandite appears.

Bradley (1928, 1929) has described widespread beds containing as much as 65% analcime extending over many hundreds of square miles in two separate intermontane basins of the Eocene Green River formation of Utah, Colorado and Wyoming. He showed convincingly that the analcime was formed by reaction and replacement penecontemporaneously with deposition of ash in saline lakes. Hydrothermal action was in no way responsible. Salt crystal moulds in near-by





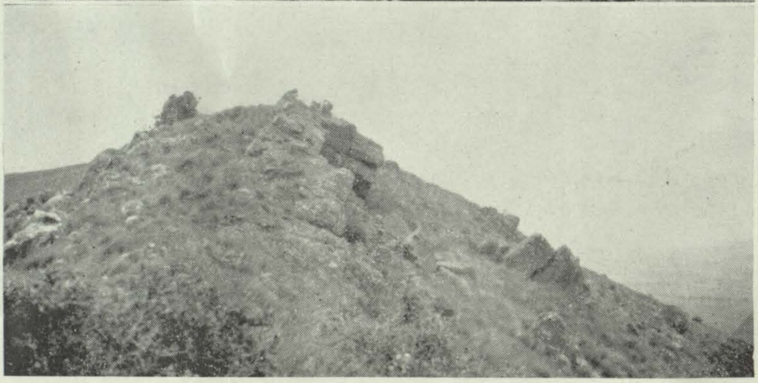


FIG. 1.—North Range (2,120 feet) showing hog-back ridges of resistant Lower to Middle Triassic meta-andesitic tuffs. It is separated by a broad belt of siltstones from White Hill (Kaihikuan and higher stages) to the left. View looking N.N.W.

FIG. 2.—Spheroidal quartz-albite-adularia metasomatite showing concentric veining, in laumontitized tuff. Bed NR_2, North Range.

FIG. 3.—Steeply dipping bed of laumontitized ash, 10 feet thick, with detached joint blocks littering slope to the right. NR_5, North Range.

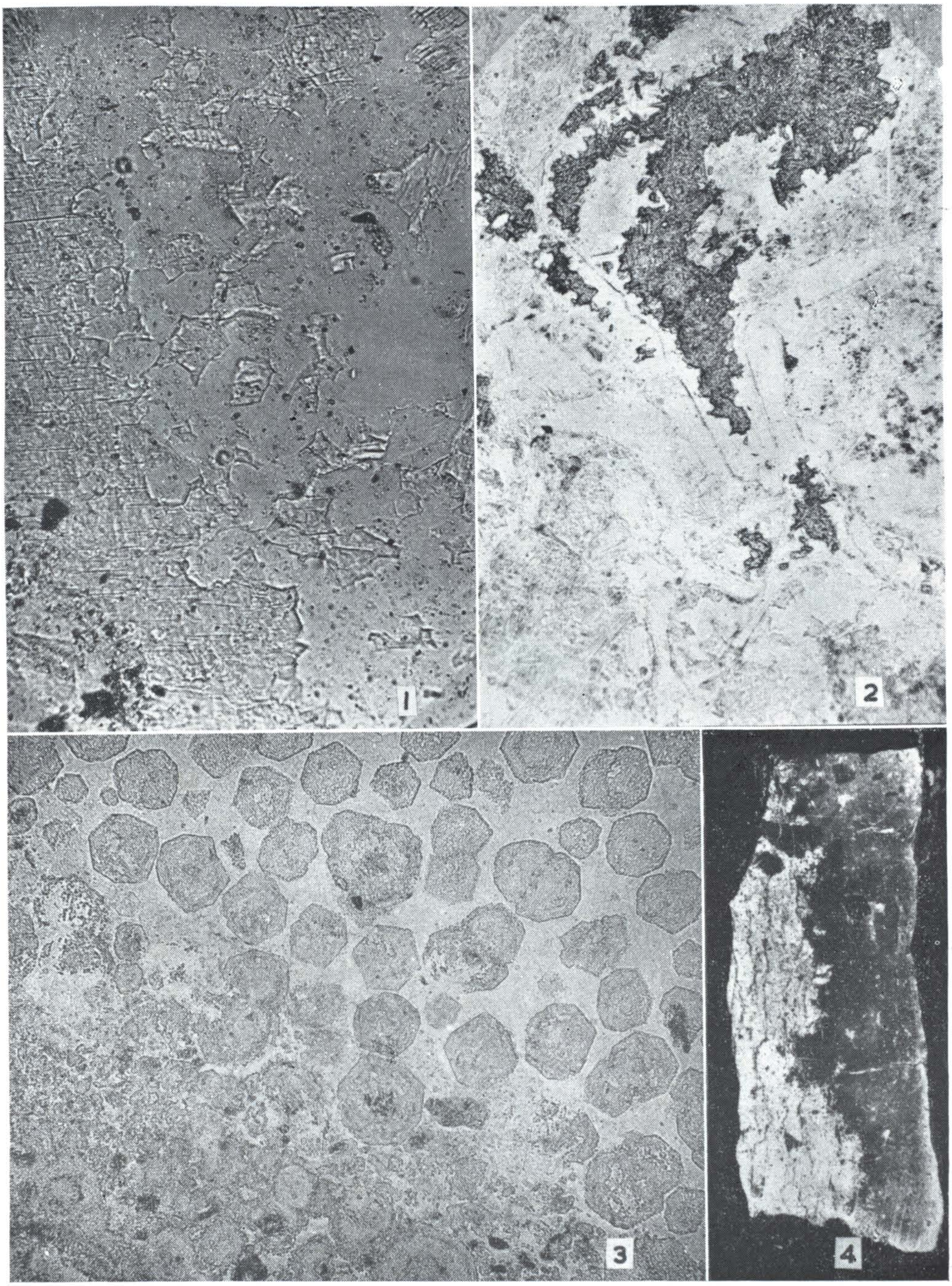


FIG. 1.—Granular mosaic of quartz (low relief) replacing laumontite (strong negative relief and good cleavage). 8784, NR_5, North Range. Ordinary light, X150.

FIG. 2.—Aggregate of pumpellyite (dark grey) in metasomatite. Secondary quartz (colourless) and feldspars (light grey) preserve ghost-like traces of ash structure. 8818, NR_2, North Range. Ordinary light, X100.

FIG. 3.—Icositetrahedral pseudomorphs of feldspars after analcime set in quartz. 8824, NR_2, North Range. Ordinary light, X100.

FIG. 4.—Contact between laumontitized tuff (light) and quartz-albite-adularia metasomatite (dark). Dark streaks of quartz and adularia occur in laumontite near the contact and roughly parallel to it. 8799, NR_2, North Range. Almost natural size.

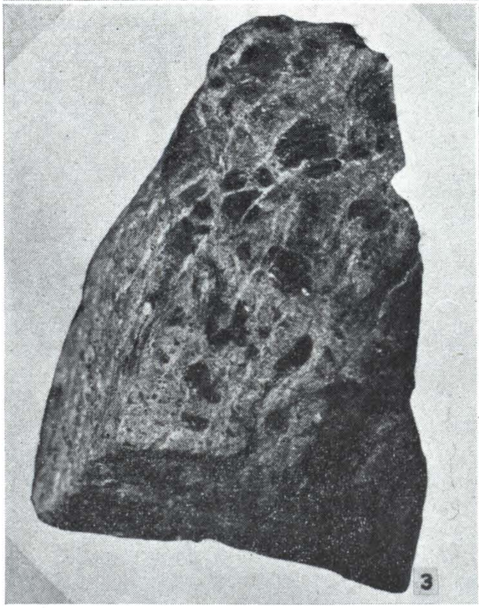


FIG. 1.—Tuffaceous greywacke. Meta-andesitic rock debris and loose crystals of albitized plagioclase and rarer augite in a base rich in chlorite and leucoxene. 8932, NR_5, North Range. Ordinary light, X29.

FIG. 2.—Fine rhyodacite vitric tuff. Small cuspate glass particles have devitrified to heulandite, often darkened with iron oxides. A large clear crystal of andesine is near the top and smaller fragments are in the groundmass. 9035, 100 feet below top of Oretian, Wether Hill. Ordinary light, X23.

FIG. 3.—Quartz-albite-adularia metasomatite showing some large lapilli (dark) cut by anastomosing veinlets of secondary feldspar. NR_2, North Range. X4/5.

FIG. 4.—Felt of secondary albite in metasomatite, with a few large albitized plagioclase fragments. 8814, NR_2, North Range. Crossed nicols, X90.

beds prove the high salinity of the lake waters. Similarly, Ross (1928, 1941) has described a bed of " sedimentary analcite " from West Yavapai county, Arizona, formed where tuffs have fallen into and reacted with saline playa lake waters.

Rengarten (1940) has found authigenic analcime deposited around fragments of decomposed porphyrite in Permian sandstones from Russia and as minute crystals in the gypsum and carbonate matrix It is considered to have been formed during the deposition of the sandstone and the evidence of high salinity will again be noticed. Again, Keller (1952) considers that a zone of analcime-rock in Triassic mudstones in Wyoming is due to the action of strong saline solutions on clay, which was perhaps derived from volcanic tuff

It seems clear that analcime may be formed by the attack of highly saline waters on volcanic glass at atmospheric temperatures. The Taringatura analcimized tuffs are interbedded with marine fossil bands. Evidence to show whether normal sea water at normal temperatures will bring about analcimization of glass is inconclusive, although Raw (1943) considered that analcime has been formed in palagonite tuffs from Jamaica by the action of salt sea water. On the other hand, the lime-rich zeolite phillipsite was found by the Challenger Expedition (Murray and Renard, 1891, pp. 400–412) to be widely distributed in deep-sea deposits and was apparently formed by reaction with basic glass at temperatures fluctuating 2–3° C above and below zero. Bramlette and Bradley (1940) also recorded phillipsite (?) rather than analcime in deep-sea cores from the floor of the North Atlantic

It is believed that in the Taringatura sediments, analcime, like heulandite, has been formed from volcanic ash either penecontemporaneously with deposition or at moderate depths of burial, and that sea water or connate waters must have provided the additional sodium for its formation.

STILBITE

Stilbite occasionally fills joint fractures in rocks of the North Range. It occurs in small, characteristic (010) tablets, often twinned on (100) The optic axial plane is parallel to (010); (—) 2V is small to moderate.

$$\alpha = 1\cdot493 \pm \cdot002 \qquad \alpha \wedge c = 5° - 10°.$$
$$\gamma = 1\cdot504 \quad ,,$$

The joints post-date the formation of laumontite, heulandite and analcime, and the stilbite is of still later formation.

PUMPELLYITE

Pumpellyite is a normal constituent of the quartz-albite adularia metasomatites in the NR_2 tuffs (Plate 2, Fig. 2). It also occurs in albitized tuffaceous greywackes in the lower part of the Taringatura section, the highest occurrence observed being 1,150 feet above the base of the Kaihikuan Stage. An extended description of the mineralogy of pumpellyite has been published elsewhere (Coombs, 1953, pages 128–130 for North Range material)

PREHNITE, EPIDOTE, CALCITE

All three of these minerals occur spasmodically in the North Range beds, more especially in the albitized lithic tuffs in which calcite is a fairly constant accessory They represent lime and alumina released during albitization of andesine, although a carbonate mineral also occurs as pseudomorphs after pyroxene in a few rocks. Small aggregates and dusty granules of authigenic ferriferous epidote are widespread, even up into the Otapirian (9064), but epidote is never abundant. The fact that the more hydrous lime silicates, laumontite, pumpellyite and prehnite are more characteristic reflects the low temperature at which alteration occurred. Even these minerals are rare or absent in Upper Triassic rocks

SPHENE

In all albitized rocks and in some unalbitized ones, ilmenite is found to be in process of alteration. Films of leucoxene appear, but quite commonly titanium has been taken into solution and reprecipitated elsewhere as small granules, which whenever large enough to test, give the characteristic interference figure of sphene and show its other properties. The mineral often occurs as spongy crystals, 0 05 mm. diameter, or sometimes even as radiating or semi-fibrous aggregates

Chemical analyses (Table VIII) show that the altered vitric tuffs of the North Range carry considerably less titanium than the associated lithic tuffs, due mainly to the rather more acidic character of the former and partly to their better-sorted nature. The four analysed quartz-feldspar metasomatites show significantly less titanium than the heulandite rocks Detrital titaniferous iron ore present in the heulandite rocks has been partially destroyed in the quartz-feldspar rocks and titanium removed in solution In other cases, however, there is a strong tendency for secondary sphene to crystallize along with secondary albite Thus in a laumontite-bearing tuff (8940) from the upper parts of the North Range beds secondary sphene occurs abundantly, usually in small pools of secondary quartz and albite. The components of sphene are evidently very mobile in low temperature solutions.

CELADONITE

In the heulanditized tuffs, and to a lesser extent in other North Range rocks, celadonite is important as fibro-lamellar interstitial films and radiating aggregates that sometimes make up amygdales In the latter case successive concentric zones vary slightly in colour and refractive indices, and sometimes a few flakes of a greenish brown micaceous mineral occur at the centre (8795). The following optical properties were determined (8768) :—

$$\alpha = 1\ 580 - 1\ 595 \pm\ 005$$
$$\gamma = 1\ 605 - 1\ 620$$
$$(-)\ 2V = \text{very small}$$

Pleochroism: α = pale yellow to yellowish green

$\beta = \gamma =$ deep bluish green.

The material gave an X-ray powder pattern indistinguishable from that of celadonite from Vesuvius (Maegdefrau and Hoffman, 1937)

In a review of the glauconite and celadonite minerals, Hendricks and Ross (1941) point out that reducing conditions are required for their formation, and it is noticeable that the ratio Fe_2O_3 : FeO is low in the heulanditized tuffs ($1 . 2\frac{1}{4}$), but becomes large in the laumontitized tuffs and quartz-albite-adularia metasomatites (3–4 .1), in which celadonite is much less important.

Chlorite

Most Taringatura rocks contain a variety of chloritic minerals of relatively high birefringence and uniformly negative sign. They occur as interstitial films and as small spherulitic aggregates. A relatively homogeneous example occurs in an amygdaloidal meta-andesite conglomerate pebble (9871). The degree of crystallinity and the birefringence both reach their highest development in the centres of the amygdales, where the following properties were determined:—

$$\alpha \text{ (very pale yellow)} = 1\ 610 \pm \cdot 005$$
$$\gamma \text{ (yellow-green)} = 1\ 623 \pm 005$$

A powder photograph of this material showed a typical chlorite pattern, although the optical properties do not fit into an occupied field in Winchell's classification of the chlorites (1936, Fig. 4). Winchell points out that a high ferric iron content raises both the birefringence and the refractive indices with respect to more normal chlorites, and it is probable that the Taringatura chlorites are rich in ferric iron This may be due either to oxidation from the ferrous state (see Winchell, 1936) or to original ferric iron replacing aluminium (Hallimond, 1939, p. 453)

In some other Taringatura specimens the birefringence becomes still higher and the colour passes through brownish green, almost to browns, with γ as high as 1 67. A detailed study of these products has not been attempted.

Clay Minerals (Kaolinite, Montmorillonite-Nontronite)

Clay minerals are present in small amount in most Taringatura rocks, as is shown by staining with methylene blue In pseudomorphs after analcime in the quartz-albite-adularia metasomatite 8824, a colourless clay mineral of low birefringence accompanies adularia, although it is difficult to decide whether it was formed during early metasomatic alteration of the rock or during geologically recent weathering. Among other quartz-albite-adularia metasomatites, 8831 is unusual on account of the relatively high proportion of a very pale green birefringent clay mineral which it contains in a system of closely spaced, branching microscopic films. Dr. R. J. McLaughlin kindly carried out differential thermal analyses of these two specimens and reports kaolin in the former and a montmorillonite-group mineral in the latter. The green colour of this mineral and its refractive indices, $\gamma = 1\ 595$, $\alpha = 1\ 570$, show that it is an iron-bearing member of the montmorillonite-nontronite series (Ross and Hendricks, 1945, Fig. 9, p. 56) Nontronitic films appear to be present in the majority of heulandite-bearing tuffs, but become less important or disappear in most quartz-albite-adularia metasomatites. The association with heulandite may be compared with the occurrence of "clinoptilolite" in many bentonites as already discussed

Ross and Hendricks (1945) consider that the formation of bentonite requires prolonged leaching of alkalies and silica by ground water or perhaps by sea or lake waters containing a ready supply of magnesium and ferric iron. As has been shown, the alteration of Taringatura tuffs to heulandite required little change apart from loss of soda Fenner (1936) found in the Geyser region of Yellowstone National Park that kaolin was formed under the influence of acid waters, beidellite-montmorillonite under the influence of alkaline waters It was from alkaline waters, too, that the zeolites heulandite and analcime were formed. A similar relationship may well have held at Taringatura

PYRITE

Authigenic pyrite occurs as small scattered grains in some of the greywackes and indurated mudstones, especially in the North Range beds, but it is never in large amount.

AUGITE

Augite is the characteristic detrital ferromagnesian constituent of the andesitic tuffs. Although some grains in the lithic tuffs may be partly or completely altered, many grains are still essentially quite fresh and pseudomorphs are readily recognizable as such. Frequently, both augite and hornblende show "cockscomb" structure (Ross, Miser and Stephenson, 1929) consisting of jagged terminations and embayments due to intraformational solution In Ross's examples the augite is replaced by calcite. This is the case in a few Taringatura examples, but replacement by feldspars, quartz or zeolites is more usual. Sometimes these minerals completely penetrate the host, which is broken up into separate residua in optically parallel positions. Augite occurs in the heulandite- and laumontite-bearing vitric tuffs, but in the quartz-feldspar metasomatites it is completely destroyed. This proves conclusively that the zeolite rocks are not alteration products of the quartz-feldspar rocks.

ACCESSORY DETRITAL MINERALS

A study of heavy mineral concentrates is outside the scope of the present work. Such minerals as zircon and apatite that is often dichroic, are present in most thin sections, and detrital hornblende, tourmaline, sphene and epidote are also found.

PETROGRAPHY

A. THE CONGLOMERATES OF THE NORTH RANGE BEDS

The pebbles in the North Range conglomerates are almost entirely of volcanic origin, and they undoubtedly represent rock types that have contributed to the formation of the tuffs. The tuffaceous greywackes, as distinct from the purely pyroclastic rocks, may have been formed by the accumulation of debris derived from mechanical weathering of a terrain made up of flows of such rocks. Textures in the groundmass of the pebbles correspond with those of small fragments in the tuffs and greywackes, whereas phenocrysts of the pebbles correspond with separate crystals in the sediments.

In the Hokonui Hills about 12 miles south-eastwards along the strike from where the main North Range conglomerate collection was made, Mr. I. C. McKellar has collected pebbles from the local development of the NR_3 beds. (Grid reference Prov. 1 ml. Series S.160/453645). Of seven thin sections of pebbles from this collection, only one is albitized. In the rest, feldspar may show slight alteration along cracks and cleavages, but on the whole it retains its original fresh condition. The collection may be listed as follows:—

9850. *Feldspathic basalt.* Small seriate phenocrysts of labradorite, zoned $An_{71 \rightarrow 55}$, with very thin, more acid mantles An_{30}; numerous microphenocrysts of augite.

9852, 9853. *Augite andesites.* Plagioclase phenocrysts zoned $An_{53 \rightarrow 43}$; augite $2V = 53–50°$, sometimes zoned; pilotaxitic groundmass.

9847. *Augite andesite.* Zoned phenocrysts of andesine, ½–3 mm. long, composition An_{45-37}, sometimes partly altered or with clouded oligoclase border zones; groundmass feldspar partly albitic. Abundant seriate microphenocrysts of augite, $2V = 53 \rightarrow 49°$, $\beta = 1{\cdot}696–1{\cdot}699 \pm {\cdot}002$ corresponding to compositions $Ca_{44}Mg_{36}Fe_{20}$ — $Ca_{39}Mg_{37}Fe_{24}$. Rare large, mostly resorbed phenocrysts of hornblende.

9849. *Leucocratic andesite.* Scattered microphenocrysts of andesine or andesine-labradorite with oscillatory zoning ranging in composition from An_{55} to An_{37}, often with relatively acid cores (An_{37-40}) followed by more calcic zones and then a more acid margin. Rare crystals of green hornblende, largely resorbed. Groundmass of andesine laths in micropoikilitic alkali feldspar.

9846. *Albitized augite meta-andesite.* Corresponds to the augite andesite above, but the plagioclase is albite, An_{0-4} with faint clouding and sericite inclusions.

9848. *Meta-andesite* with actinolite. Plagioclase is zoned An_{45-28}, but has undergone incipient granulation and recrystallization into disoriented units. There are abundant needles of actinolite, and small amounts of secondary quartz. The metamorphism of this pebble is pre-depositional.

Several of the above rocks are amygdaloidal, the vesicles being filled with chloritic minerals. The pyroxene may be quite fresh or may be pseudomorphed by carbonate, chlorite or celadonite. Sometimes only the core is altered in this way. All slides contain accessory iron ores and apatite; most show some leucoxene or recognizable secondary sphene.

In the North Range conglomerates are found the albitized equivalents of these Hokonui pebbles and in only one of 12 specimens sectioned does lime-bearing plagioclase remain. In other cases plagioclase phenocrysts are typically clouded, are studded with sericite, and have the composition An_{0-4}. The commonest varieties are augite meta-andesite (e.g., 8895), but they range to an acid rock (8890) in which phenocrysts of clouded albite are enclosed in a banded, microspherulitic groundmass. Staining shows that this groundmass is very rich in potash feldspar, and parts of it preserve perlitic fractures. Two pebbles were found of older consolidated tuffs, themselves of andesitic origin.

It is interesting to note that pebbles described by Watters (1952) from conglomerates of approximately the same age in the Eastern Hokonuis vary about a distinctly more acid mean than the Taringatura pebbles, quartz keratophyres being prominent. On the other hand the general effects of alteration in the tuffaceous greywackes of the Eastern Hokonuis are similar to the effects at Taringatura, and tuffs with laumontite and other zeolites are included in the pre-Kaihikuan sequence, though apparently not in the abundance of Taringatura.

B. THE LITHIC TUFFS AND TUFFACEOUS GREYWACKES OF THE NORTH RANGE BEDS

These rocks reach a total thickness of nearly 5,000 feet. They consist of small angular fragments of fine-grained volcanic rocks corresponding in texture to the conglomerate pebbles already described, with an admixture of separate crystals (plagioclase, augite, ores) and either of pumiceous lapilli in the more pyroclastic rocks or of fragments of non-volcanic origin in the tuffaceous greywackes. They are well indurated and show a rather uniform dark greyish-blue colour in hand specimen. Three typical specimens have been analysed.

Of these, 8871 consists of an aggregate of rock, altered glass and crystal fragments, each about ¼-¾ mm. diameter. Most abundant are lithic fragments that are pilotaxitic or almost trachytoid in texture and are made up of small laths of andesine, subordinate granular augite or its alteration products, interstitial iron ores and dusty leucoxene. A few fragments contain a very small amount of interstitial alkali feldspar, and in some the groundmass is almost opaque with dusty magnetite or hematite. One more acid fragment was observed to be microspherulitic in texture. Many devitrified glass fragments are quite pumiceous and during explosion of the magma have had their gas bubbles drawn out into tubular capillary-like vesicles which are now infilled with rather poorly crystalline chlorite of spherulitic habit accompanied by celadonite. Chlorite thoroughly impregnates the rock and also replaces some of the glass, although minutely fibrous aggregates of heulandite are more important in this respect. Many of the devitrified shards contain small phenocrysts of andesine, and rare tiny crystals of secondary albite can also be recognized. Epidote is a minor constituent. Scattered loose grains of augite and magnetite and rarer hornblende occur through the rock and one decomposing flake of biotite was found, but the commonest detrital crystal fragments are andesine, often with normal or oscillatory zoning and ranging in composition from An_{50} to An_{32}. These andesine crystals are often quite fresh and clear apart from acicular inclusions of apatite, but in the neighbourhood of cracks and cleavages they often contain irregular patches that are albitic and contain sericite inclusions. With more advanced alteration, jagged, isolated patches of andesine are found in optical continuity within pseudomorphous albite It is quite possible that some of the albitic fragments were derived from previously albitized material, either from the walls of the volcanic vents during explosive eruption, or from other sources during subaqueous sorting and deposition Nevertheless the fact that "islands" of andesine-bearing rock such as the one represented by this rock, occur scattered through the North Range beds, shows that predominantly andesitic material was accumulating and that most of the albitization of the North Range beds must have occurred in place, a fact confirmed by the comparison between the Hokonui and North Range conglomerates.

TABLE III

Analyses of Meta-andesite Tuffs from the North Range, and of Comparable Rocks.

	A	*B*	*C*	*D*	*E*	*F*	*G*
SiO_2	57 13	56.56	55.75	53 86	55.86	51.22	57.50
TiO_2	1.27	1 52	1.34	0.72	1.60	3.32	0.79
Al_2O_3	16 03	15.24	16.16	14.75	15.17	13.66	17.33
Fe_2O_3	3.17	3 28	1.25	3 94	2.54	2.84	3.78
FeO	5.35	5 46	7 34	5 90	6.98	9.20	3.62
MnO	0 10	0.12	0.12	0.14	0 19	0.25	0.22
MgO	2 51	2.60	3 87	4.17	2.30	4 55	2.86
CaO	4 00	3 77	3 50	7 17	3.39	6.89	5 83
Na_2O	3.17	5.38	4 39	5 36	5.45	4 93	3.53
K_2O	2.79	0 92	1 59	0.46	2.05	0 75	2 36
H_2O+	3.27	2.54	3.51	2.53	2.53	1.88	1.88
H_2O-	0.78	0.75	0.72	0.92	1.21		
P_2O_5	0.23	0.22	0.30	0.16	0.63	0.29	0.30
CO_2	0.09	1.37	0.44	tr	tr	0.94	
BaO	0.06	0.004	0.02	nil	0.05		
	99.95	99.73	100.30	(100.15)	(100.07)	100 72	100.00

A. 8871. Andesite lithic tuff, some heulandite replacing glass; bed NR_1, North Range, Taringatura S D (BaO determined spectrographically)

B. 8873. Albitized lithic tuff; bed NR_1, North Range. (BaO determined spectrographically.)

C. 8932. Albitic tuffaceous greywacke; bed NR_5, North Range (BaO determined spectrographically.)

D. Spilite; 4 mls. N of West Dome, Mossburn district, Southland, New Zealand Analyst: F. T. Seelye. (Reed, 1950, p. 116). (V_2O_3=0.043%, S=0 03)

E. Andesite; Mount Camel, Hohoura, North Auckland. Analyst· F T. Seelye (Bartrum, 1929.) (ZrO_2 = 0.03%, S = 0.09, Cr_2O_3 = nil, NiO = 0.01 SrO = 0 02, O for S = 0 03.)

F. Average spilite. (Sundius, 1930, p. 9)

G Average augite andesite. (Daly, 1910, p. 223)

Considering the water-sorted, pyroclastic origin of the rock and its mildly altered condition, the analysis compares remarkably closely with Daly's average augite andesite (Table III). One distinction is that the lime content of the Taringatura rock is decidedly low (4 00% against 5.83%). This can be correlated with the partial albitization of some of the plagioclase, without the formation of corresponding amounts of other lime-bearing minerals *in situ*

Bedded sharply against the above rock in the same hand specimen and thin section, but not included in the analysis, is a fine tuffaceous siltstone containing conspicuous heulanditized ash particles, crystals of andesine and augite and flakes of sericite.

Specimen 8873 (analysis B, Table III) is believed to have been a rock initially closely similar to 8871 and it comes from the same beds, NR_1 In this specimen, however, plagioclase is uniformly albitized, $An_{0\text{-}4}$, with sericite and some chloritic inclusions. It contains rather more calcite than is normal, but is otherwise typical of a North Range albitized lithic tuff. Destruction of titanium-bearing minerals has proceeded a stage further than in 8871 and heavy films of " leucoxene," probably sphene, have been deposited round the margins of grains, even round the edges of albite crystals as a result of solution and redeposition. A richly ferriferous epidote is rather more abundant than in the preceding rock, but is still a minor constituent. Zeolites and potash feldspar are absent. Calcite, albite, and chlorite have replaced glass.

Specimen 8932 (Plate 3, Fig. 1; and analysis C, Table III) is typical of the thick NR_5 beds of tuffaceous greywackes in which glass fragments are less common and in which there are occasional grains of quartz and fine-grained hornfelsic and slaty rocks. Furthermore, some of the grains show a tendency towards rounding in contrast to the high degree of angularity in the previously described rocks. There is a particularly heavy development of " leucoxene "-rich interstitial films. Other slight differences between 8932 and the albitized lithic tuff 8873, may be summarized as follows. (a) Magnetite is less abundant in 8932 whereas augite is rather more common. This fact is reflected in higher FeO and lower Fe_2O_3 in the analysis of 8932 and by corresponding changes in the norm (Table IX). (b) Calcite is much less common, but prehnite occurs in significant amount as bundles of (001) tablets sieved with a mineral of low refractive index, probably albite. It may be noted here that in other rocks of this group certain other lime-bearing silicates appear, usually in small amount. Thus pumpellyite occurs in the matrix of the volcanic conglomerate in NR_3 (8887) and laumontite occurs in 8918 (c) In spite of the presence of scattered grains of detrital quartz, the rock has a distinctly lower silica content than the other analysed meta-andesite tuffs, suggesting that the volcanic contribution represents on the average a slightly more basic magma than 8871 and 8873.

C. The Vitric and Crystal-Vitric Tuffs of the North Range Beds

Type I. Heulandite-bearing rocks

Coarse heulanditized vitric to crystal-vitric tuffs occur as subordinate members of the laumontite rocks of the 450 feet thick NR_2 beds, and fine-grained vitric tuffs altered to heulandite and laumontite occur as numerous thin beds throughout the North Range series.

The coarser heulandite rocks, such as the analysed specimen 8768 (Table VIII), show beautifully preserved vitroclastic structure (Pirsson, 1915), the margins of cuspate ash particles being traced out and emphasized by films of deep blue-green celadonite and chloritic and clay minerals. Glass has been entirely destroyed. Minutely fibro-lamellar and feebly birefringent heulandite is much the most important replacement product. Sometimes it is faintly pink in colour due to the presence of dusty iron oxides precipitated during devitrification. In some cases clear secondary albite replaces part or all of the glass in a given shard, heulandite replacing the rest and in one exceptional heulanditized tuff (8770), calcite is abundant. Staining proves that many devitrified or finely crystalline shards and lapilli, especially the larger ones, are rich in potash feldspar.

Whether they occur as isolated crystals or as phenocrysts in scattered lithic fragments, the majority of plagioclase grains are found to be clear and glassy. They represent the phenocrysts of the exploding magma in their unaltered condition. In the analysed rock, 8768, plagioclase ranges in composition from An_{36} to An_{51} and often shows oscillatory zoning, but in the otherwise similar rocks, 8767, 8772, compositions vary about a distinctly more sodic mean, ranging from An_{29} to An_{38}, suggesting that the 450ft. bed contains tuffs erupted at slightly different stages of magmatic evolution although always of acid andesitic aspect. Other plagioclases in the rock are cloudy and albitic, probably due in part to incipient alteration in place and in part to an admixture of earlier formed albite. Free crystals of augite have the optical properties $2V = 50 - 53\frac{1}{2}°$, $\beta = 1.696 - 1{\cdot}700$, closely comparable to those from the augite andesite conglomerate pebble 9847. Hornblende is much less common and accessory apatite, zircon and quartz are found, the latter, at least in part, being of older, metamorphic origin.

The thin-bedded fine vitric tuffs with heulandite such as the analysed specimen 8776 (Table VIII), and a similar one containing fragmentary plant remains, 8766, call for little special mention. As is to be expected in very fine-grained, well-sorted sediments, stony fragments and heavy minerals are less conspicuous than in the coarser tuffs On the other hand tiny wisps of decomposing biotite are noticeable.

The heulandite tuffs are of special interest as they are the least altered of the vitric tuffs available for study. Apart from accessory hornblende, the associated phenocrysts are comparable to those of the andesitic lithic tuffs and phenocrystic quartz appears to be absent.

Subaqueous transport and sorting of tuffs can bring about a compositional differentiation to some extent, irrespective of changes in the composition of the parent magma, but nevertheless, the higher SiO_2 and lower TiO_2 and Al_2O_3 of the vitric tuffs suggest that they have been derived from a distinctly more acid magma nearer to dacite in composition than that which gave rise to the lithic tuffs.

Type II. Laumontite-bearing rocks

Both the fine-grained, thinly-bedded vitric tuffs that occur throughout the North Range beds and the coarse vitric to crystal-vitric tuffs of the bed NR_2, have undergone laumontitization as their principle mode of alteration. In all respects except those inherent in the alteration they correspond exactly with the heulanditized tuffs just described. Between crossed nicols, however, the analysed rock 8791 is seen to consist of a mosaic of approximately equidimensional laumontite grains, 0 1–0 3 mm. diameter. Andesine fragments in the heulandite rock are represented by a few small albite pseudomorphs and blue-green celadonite is partly replaced by greenish-brown birefringent ferruginous films. Small scattered pools of secondary quartz are found and a few thin laminae relatively rich in silty material cross the specimen If the assumption is made as a first approximation that all the lime, alkalies and water of the analysis 8791 (Table VIII) are contained in the laumontite, it is possible to calculate an upper limit of 73% on the amount of laumontite in the rock. The actual percentage of laumontite must be rather less than the calculated figure, though of the same order.

In another specimen, 8940, the laumontite units are much bigger, have undulose extinction, and are riddled with tiny clusters of twinned crystals of secondary albite and of quartz, either separately or together. The albite crystals reach lengths of 0·3 mm., the quartz grains usually much less. In this rock, as already mentioned, secondary sphene accompanies the quartz and albite in noteworthy amount. Again, in 8784, large laumontite crystals are sieved with minute doubly terminated prisms of secondary quartz which here and there coalesce into granular mosaics (Plate 2, Fig 1) Secondary albite and a few small grains of epidote are present as well.

The coarse laumontitized tuffs of the bed NR_2 are represented by 8795 and 8802. They correspond to the heulandite rock 8768 except that large crystals of laumontite, several millimetres in diameter, take the place of heulandite, each crystal enclosing many ash particles (Coombs, 1952, Fig. 1). Celadonite is much less abundant than in the heulandite rocks and brownish-green or greenish-brown chloritic minerals of moderate to high birefringence are prevalent. Tiny pools of authigenic quartz and feldspar occur scattered through the slides. Stony fragments and loose crystals of augite, magnetite and ilmenite, rare hornblende and heavy accessories, especially zircon, occur as in the coarse heulandite rock, but detrital plagioclase is uniformly albitized with faint clouding and sericite inclusions.

The analysed rock 8800 is similar to the last two in most essentials, but contains more stony fragments and loose crystals and more secondary quartz and feldspars, facts reflected by the lower water content and higher specific gravity of this rock as compared with the other analysed laumontite rock, 8791. The secondary quartz has a marked tendency to occur as minute stubby prisms projecting into the laumontite of devitrified shards from the intergranular films. It seems that the interstices between original glass fragments have acted as channels along which the silica-bearing solutions could migrate. The rock represents an early stage in the transition of the laumontite-bearing rocks to the Type III quartz-albite-adularia rocks, and its analysis is notable for higher silica, higher alkalies, lower lime and alumina than 8791.

The transition can be observed in specimens 8797, 8798 and 8799. The oblate-spheroidal shape of many of the quartz-albite-adularia masses has already been described, as has the concentric arrangement of feldspar-rich veinlets within them. Minute, veinlet-like films of quartz and adularia commonly lie parallel to the general trend of the irregular contacts between the quartz-albite-adularia metasomatites and the surrounding laumontite rock (Plate 2, Fig. 4). Thus, although the actual contact is sharp, the laumontite rock in the neighbourhood of the metasomatites is itself enriched in quartz and feldspar.

Type III. Quartz-albite-adularia rocks

Hard, compact aggregates, several feet in diameter, of quartz, albite and adularia with important accessory pumpellyite occur throughout the laumontitized bed of coarse vitric tuffs, NR_2. They are usually light green in colour, but may be fawn-coloured or even pink. Features observable in the surrounding tuffs such as bedding structures, plagioclase crystal fragments and large lapilli with scattered feldspar phenocrysts, are usually clearly visible in the hand specimen (Plate 3, Fig. 3). Sometimes, however, networks of veinlets of albite or adularia with or without quartz are so close-set and so plentiful that earlier structures are obscured. In thin sections albitized plagioclase crystals with sericite inclusions are seen to occur just as in the laumontite rocks, a few grains of decomposing iron ores are found, and stony fragments may be recognizable. On the other hand augite and hornblende are entirely absent and are not even preserved as recognizable pseudomorphs.

In hand specimen, the analysed rock 8819 contains coarse and fine layers cut by close-set crudely concentric veinlets which are transverse to the bedding These veinlets are poorly defined. less than one millimetre thick and are inconspicuous until stained with sodium cobaltinitrite after treatment with hydrofluoric acid. They consist of tiny crystals of adularia 0 01–0 02 mm. diameter with minor quartz and scaly ferruginous minerals. Adularia in similarly minute crystals also occurs disseminated through the groundmass, but staining shows that its distribution is irregular. It is most abundant towards the periphery of the metasomatized mass, but this is not a general relationship in other examples. The chemical analysis represents a medium-grained layer in the potash-rich region of the rock and leads to the normative feldspar composition Or 38.8, Ab 7 2, Ce 1·0, An 1 2 weight %, with 46 3% normative quartz The presence of barium calculated as celsian is noteworthy. The normative albite is represented in the mode both by the albitized crystal fragments and by small groups of secondary albite in the groundmass Quartz, like adularia, occurs disseminated through the rock and is also concentrated into veinlet-like streaks in which individual crystals are only 0·01–0·1 mm. diameter. Pumpellyite is a minor constituent, occurring as small aggregates 0 05 mm. diameter of tiny greenish and brownish-yellow granules and prisms. It accounts for the normative anorthite.

8817 is another rather coarse tuff with graded bedding. One layer, 1 cm. thick, is extremely rich in albitized plagioclase crystals and is best described as a crystal tuff. The matrix between the crystals is quartz, subordinate secondary albite, adularia in minute lozenge-shaped crystals 0 02 mm. across, pumpellyite and the usual ferruginous alteration products One or two small aggregates of secondary ferriferous epidote were also observed. The same minerals occur in an adjacent layer of vitric tuff. This part of the specimen was sampled for analysis (Table VIII). It contains more quartz, albite and pumpellyite than the quartz-adularia rock 8819 just described and less adularia, features reflected in higher SiO_2, CaO and Na_2O and lower Al_2O_3 and K_2O, but otherwise it is a closely similar rock

In the last two rocks metasomatic adularia is concentrated in veinlets and in the groundmass In other rocks, staining tests confirm that large lapilli have been preferentially enriched in it. Thus 8827 is a coarse rock with adularized lapilli up to 2 cm. diameter more or less flattened parallel to the bedding planes. Smaller shards and loose albitized crystals lie between, but the cement is mainly quartzose with minor adularia. A similar phenomenon can be observed in 8818, although here twinned secondary albite is very conspicuous in the groundmass and pumpellyite is particularly well developed. The larger lapilli are very fine grained, of uniform brownish-green colour in hand specimen and easily separable from the matrix by hand-picking from a coarse crush of the rock. The only phenocrysts in them are albitized plagioclase ($An_{0\cdot4}$). Alkalies were determined on a concentrate of this material, with the result 10 47% K_2O, 1 41% Na_2O. This gives a much greater K/Na ratio than is found in the groundmass of any normal volcanic rock, certainly much greater than in a rock in which the only phenocrysts are plagioclase.

The above rocks grade with all transitions into types such as 8814, 8829, 8859 (analysed) which are rich in secondary albite and contain little adularia. Pale pinkish phenocrystic feldspars and close-set anastomosing veinlets are visible in the hand specimen as in 8819, but the veinlets here consist of albite ($An_{0\cdot3}$) occurring as a felt of lath-shaped twinned crystals up to a length of 0 2–0 3 mm. (Plate 3, Fig. 4). Being relatively coarse-grained, secondary albite of this type almost obliterates vitroclastic structure, but enough remains to prove replacement origin Secondary quartz, pumpellyite and the usual scaly ferruginous minerals occur scattered through the sections.

The other albite-rich metasomatite chosen for analysis differs in several respects. The hand specimen is whitish, but is marked by limonitic stains and carbonaceous imprints of finely comminuted plant fragments. Vitroclastic structure is sufficiently well preserved to prove that the rock was built up of ash particles 0 1–0 4 mm. long. Pools and streaks of felted, twinned, secondary albite occur as in the last cases, but in this specimen the albite is mixed with much more secondary quartz. Staining and analysis shows that adularia is quite subordinate and it is of irregular distribution.

A few specimens are cut by quartzose veinlets ¼–4 mm. thick packed with pseudomorphs of albite (8828) and/or adularia (8824, 8830, 8860) after analcime, as reported in the mineralogy section. They provide further evidence that the period of potash metasomatism followed the formation of analcime

D TUFFS AND GREYWACKES OF LATE MIDDLE TO UPPER TRIASSIC AGE

The influx of plutonic debris and the presence of dacite and rhyolite tuffs among these rocks have already been recorded. The main points of metamorphic interest are the increasing proportion of unaltered lime-plagioclase towards the top of the section, the increasing scarcity of lime-bearing alteration products other than heulandite, and the abundance of analcime and heulandite replacing glass.

a. *The greywackes*

Although containing less quartz than most described greywackes, those of Taringatura accord with the requirements of the definition given by the Committee on Sedimentation (*Rpt. Comm. Sed.,* 1935-36, Nat. Res. Council, 1936, p. 31)—"a sandstone composed of 33 or more per cent. of easily destroyed minerals and rock fragments . . ." and they also contain more than 20% of muddy matrix or authigenic derivatives as insisted by Pettijohn (1949). Point-counter analyses of thin sections of three Upper Triassic greywackes follow:

	8952 (*Kaihikuan*)	9058 (*Warepan*)	9064 (*Otapirian*)
Feldspar	20%	28%	30%
Quartz	< 1	6	7
Volcanic rock fragments	37	15	25
Other rock fragments	8	12	15
Ores, biotite, apatite	1	1	< 1
Carbonate cement ..	—	8	—
Matrix, < 0.02 mm.	33	30	23

Of the feldspars, plagioclase greatly predominates over orthoclase. The recognizable fragments range from andesitic to rhyolitic and it is probable that under the heading "other rock fragments", numerous grains of volcanic origin, too small to be identified, have been included. The remainder of the latter fraction is made up of chert, slate or fine hornfels and coarse-grained igneous rocks.

The matrix has commonly recrystallized as a more or less irresolvable aggregate of "chlorite", quartz, albite, adularia, leucoxene and sometimes epidote. In 8952 the recrystallization is on a coarser scale, and has led to the formation of some well-developed authigenic albite and of pumpellyite. Detrital plagioclase in this rock is albitized. In one or two rocks, delicate needles of apatite may be authigenic and several zeolites certainly are. Thus laumontite appears in small amounts in a few rocks such as 8970, and heulandite sometimes occurs as a fringe of tiny euhedral crystals lining interstices in crystal tuffs. The amount of matrix decreases in some specimens, which, with their correspondingly higher proportion of granitic and acid volcanic debris, grade towards arkoses. The classification is complicated by the fact that possibly all Taringatura sediments contain material directly or indirectly of pyroclastic origin.

Typical greywackes from Canterbury and North Otago ("Alpine facies" of Wellman, 1952) appear to be more normal than these Southland types. They contain more quartz, more fragments of sedimentary origin, and on the whole much less volcanic debris.

b. *Andesitic tuffs*

Andesitic tuffs, so abundant in the North Range beds, are rare in the Upper Triassic, but some specimens such as 8976 from the Kaihikuan, show andesitic affinities. In the Kaihikuan also, there are occasional greywackes (e.g., 8973, 500 feet above the base) made up of fragments of meta-andesitic aspect, rather similar to those of the North Range.

c. *Dacitic and rhyolitic tuffs*

There are numerous thin beds of fine-grained vitric dacite to rhyolite tuffs in the Upper Triassic. The most typical type of alteration of these is replacement of glass by finely fibrolamellar heulandite which is even more poorly crystalline than in the Type I tuffs of the North Range. Particularly good examples (9012, 9035) are found in several beds at the top of the Oretian on Wether Hill and White Hill. They show beautifully preserved vitroclastic structure (Plate 3, Fig. 2) with films of alteration products tracing out the heulanditized shards, which are often stained reddish with iron oxide dust. The hand specimens and outcrops are salmon-pink in colour. The other constituents are perfectly fresh andesine accompanied by biotite, hornblende, rare potash feldspar and occasional rock fragments. Coarser heulanditized dacite tuffs of greenish grey colour occur 1,200 and 2,700 feet above the base of the Otapirian.

In other specimens the place of heulandite is taken by analcime. Most of it replaces glass but, like heulandite, it also occurs interstitially in rocks that originally contained glass. It is often seen to be in course of replacement by quartz and albite, and in 9048 for example, imperfect icositetrahedral relics of analcime are penetrated by these minerals. As in the heulandite-bearing rocks, detrital plagioclase shows little or no albitization. 9051 (Otamitan, 1,000ft.) is an impure devitrified crystal-vitric tuff containing crystals of oligoclase-andesine some of which show partial alteration to albite, rarer crystals of orthoclase and quartz which are mostly of plutonic or metamorphic origin, analcimized ash and lapilli and fragments of a variety of igneous and sedimentary rocks. A partial analysis of this rock showed 6·13% Na_2O, 1·04% K_2O. A similar analcime-bearing tuffaceous greywacke from the Triassic section at Kaihiku Gorge (9108) carries 5·10% Na_2O. About 100 yards from 9051 another specimen, 9052, was collected from approximately the same horizon. This is a much finer-grained rock consisting of finely crystalline albite and quartz with scattered larger albitized crystals and subordinate chloritic and clay minerals. It is a thoroughly altered tuff and it seems clear that the albite and quartz have formed at the expense of earlier analcime. A specimen from the Warepan stage (9057) is virtually an albite rock and is probably of similar origin.

METAMORPHIC PROCESSES IN TARINGATURA

1. *General considerations*

In 1939, Rastall commented on the lack of metamorphism in several thick geosynclinal piles, and in 1940 Lyons showed that recrystallization of kaolinite was the only definite metamorphic change that had occurred in shales and arkoses that were pierced to a depth of 15,000 feet (temperature 145° C.) by a drill hole at Wasco, California. A basal Eocene horizon which was estimated to have been buried to a depth of between 15,000 and 40,000 feet in the nearby Ventura basin was also investigated. Epidote, chlorite and much of the sericite which was forming at the expense of plagioclase were here distinctly secondary. It is generally accepted that great depth of burial in such sedimentary rocks is inadequate by itself to produce startling metamorphic effects, and it would appear that shearing stress is necessary if schistosity, entirely lacking at Taringatura, is to be produced. Nevertheless the work of Lyons suggests that at least some mineralogical adjustment is to be expected. Wellman (1951) has recently insisted on a close correlation between depth of burial and metamorphism, or induration, in many New Zealand sedimentary rocks. A glance at Table I or Text-fig. 2 shows that in the sediments of Taringatura there is a clear relationship between mineralogical changes and depth of burial.

Phenomena in the upper members such as the formation of siliceous, chloritic, and clay-mineral cements, the deposition of authigenic overgrowths on feldspar and even the replacement of glass by heulandite and analcime, are to be considered as normal diagenetic processes, whereas the disappearance of analcime and the breakdown of lime-bearing plagioclase in the lower members with the formation of albite and various lime-bearing minerals, are metamorphic. Superimposed on such reconstitutive changes are metasomatic effects which have still to be discussed

The exposed Triassic section at Taringatura is stratigraphically almost 30,000 feet thick, but it does not follow that the lowest members were ever buried to this depth, as wedging of beds is important even along the strike (Coombs, 1950. Table 5). It is not known how great a cover of Jurassic rocks has been removed by erosion Some 10,500 feet of Jurassic strata are found 30 miles to the south-east in the Eastern Hokonui Hills, but they appear to be thinning towards Taringatura (Watters, 1952, p 474). Some of the lower Triassic members were tilted to a vertical position during the late Jurassic or early Cretaceous post-Hokonuian orogeny, but signs of shearing and of post-consolidational granulation are absent After the post-Hokonuian orogeny and peneplanation, Tertiary sediments were deposited on the folded Mesozoic beds, but their thickness cannot have been great enough to have been of metamorphic significance. Later earth movements have been confined to block-faulting and gentle warping. The zeolite rocks of the North Range are cleanly cut by a joint system identical with that produced by the post-Hokonuian orogeny elsewhere in Southland. As noted above, the joints have not been healed by the zeolitization, which therefore preceded the folding. The alteration is considered to have been progressive as the temperature rose under increasing overburden, and it appears to have been essentially complete by the time the load was released after the post-Hokonuian movements.

On this interpretation, zeolites that locally do occur in joints, such as stilbite at the North Range and laumontite at a road cutting in Otapirian strata near Waimumu Stream, Eastern Hokonui Hills, must be considered as of later formation than the alteration of the main mass of the sediments.

It is impossible to make an accurate estimate of the temperature attained. Van Orstrand (in Gutenberg, 1939, p. 147) concluded that an average reciprocal temperature gradient of about 50 feet per degree Fahrenheit is found down to a depth of one to two miles over a considerable portion of the sedimentary areas of the globe, but that in parts of the United States the factor may have been as great as 110 feet per degree Extrapolated to the base of a 30,000 feet pile these figures would correspond to temperatures of 330° C. and 150° C respectively. Both higher and lower temperature gradients than these are on record, and furthermore the precise depth of burial at Taringatura is not known. Suggestive of a relatively low temperature is the fact that laumontite has been reported (Fenner, 1910; Walker and Parsons, 1922; Dunham, 1933) to crystallize in the middle to late stages of zeolite paragenesis At Taringatura it is mostly, but not entirely, found below the 15,000ft. present stratigraphic level. Eskola, Vuoristo and Rankama (1937) have shown that the experimental production of albite from anorthite in sodium silicate solutions containing excess CO_2 can be carried out at temperatures at least as low as 260° C.

During normal compaction of sediments under load, connate water is progressively expelled Such water may carry a limited amount of silicates in solution and these may be deposited as authigenic quartz and feldspars in porous beds through which the water passes (Johnson, 1920). Such a process may have been of contributory importance at Taringatura and cementation phenomena are of obvious significance in the coarser-grained beds. Vast quantities of water were permanently trapped first in volcanic glass, and then in the zeolites that replaced the glass. The main factors in such metamorphism as occurred were a moderate rise in temperature under the great overburden, and a continued supply of water and relatively unstable silicates (glass and zeolites). The effects are those of hydrothermal alteration. Mineral assemblages have been developed similar in many respects to those of the Yellowstone geyser region and less markedly to the Keweenawan lavas of Lake Superior, notably in the quartz-albite-adularia-pumpellyite paragenesis (cf. Klein, 1939), even though the geological setting is quite different. There is also a close paragenetic parallel with the Wairakei thermal region of New Zealand (Steiner, 1953) where ptilolite, heulandite, analcime and adularia are developed.

Although there is a statistical trend in the relation of metamorphism to depth, the effects are irregular and spasmodic in distribution, and equilibrium is commonly not attained. There is a definite tendency for the most marked effects to be observed in the coarser-grained rocks in which movement of interstitial solutions would be facilitated.

2. *Relation to the schists of Central Otago*

The Taringatura rocks show some correspondence to the Chl. 1 subzone greywackes of the Otago schist complex, but they also show important differences and should not be classified with them. As defined by Turner (1935, 1938), Chl. 1 subzone rocks show incipient cataclasis, feldspar is saussuritized or much sericitized and epidote, chlorite, calcite, actinolite and sphene are listed as the interstitial matrix of reconstituted minerals. In the Triassic rocks of Southland, and in many Permian greywackes from the Otama-Clinton area as well, cataclasis is absent, plagioclase is often albitized but it is not saussuritized, potash feldspar is not sericitized, actinolite has not been found as a reconstitutive mineral, and the highly hydrated lime silicates laumontite, pumpellyite and prehnite occur more characteristically than epidote. The Taringatura rocks have undergone a special type of low-grade hydrothermal alteration in contrast to the dynamothermal metamorphism of the schists.

There is no general agreement on the date of the main metamorphism of the schists. In an important survey of the Permian-Jurassic rocks of New Zealand, Wellman (1952) links the sedimentation of the Otago schist belt with that of the long upper Palaeozoic—lower Jurassic sequence which has been folded along approximately parallel axes Furthermore, he points out the occurrence of Upper Triassic fossils in semi-schists at various points near the eastern margin of the Otago-Alpine schist belt, and of Permian-Carboniferous fossils similarly placed on its western margin. Turner (1938, 1940) has shown from detailed petrofabric studies that deformation of the schist proceeded in more than one stage. Hence it is possible, though unproved, that the undoubted low grade metamorphism of certain fossiliferous Triassic sediments, together with re-orientation of quartz fabrics and production of new lineations in previously metamorphosed rocks may have occurred during the great post-Hokonuian orogeny, whereas the "main" metamorphism may have taken place long before. If so, it must have occurred about the end of the Late Palaeozoic and before the Taringatura greywackes were deposited. The Late Palaeozoic intrusion of gabbros and associated acid differentiates in the Otama district and the influx of plutonic conglomerate pebbles in subsequent Permian sediments near Clinton affords one instance of the possibility of orogenic breaks in the general sequence and the absence of undoubted Lowest Triassic sediments provides another. The importance of such breaks remains to be elucidated.

At Taringatura we see that there is a general tendency for increase in alteration towards the base of the section. At first sight it might be tempting to extrapolate this through the Late Palaeozoic greywackes of the Lumsden district to the schists. This would be unjustified, and an over-simplification. The changes observed in the Taringatura rocks are believed to have been made possible, not only by mild rise in temperature following burial, but also by the exceptional quantities of water and unstable silicate material stored up in volcanic glass and zeolites. But for this, the incipiently metamorphic effects must have been much less marked. Cataclastic effects at Taringatura are entirely absent and alteration is greatest in the coarser-grained, more porous rocks.

The conditions which caused the metamorphism of the Otago schists were entirely different. "Rocks of greywacke composition were reduced to a phyllonitic condition by intense penetrative movement on slip-surfaces . . . Subsequent mineralogical reconstitution, accompanied by segregation of particular minerals into subparallel bands, was followed by renewed deformation involving slip on the old schistosity surfaces, contortion of the segregation bands . ." (Turner, 1940, p. 189). These are the effects of directed pressure, not of mere depth of burial with accompanying temperature effects. The metamorphic phenomena at Taringatura differ not only in degree but also in kind, when compared with those of the schists

There can be no doubt that sediments subjected to orogenic movements with shearing stress will be much more strongly metamorphosed than non-deformed sediments at the same depth of burial. Although in essentially undeformed basins an increase in rank may be observed with depth, this relationship cannot safely be extended to deformed rocks, or less water-rich rocks, even though in many individual cases the generalization may appear to hold.

3. *Heulandite and analcime rocks*

It has been seen that heulandite is to be recognized as a widespread devitrification product of intermediate to acid volcanic glass formed with little change in chemical composition under the influence of ground or connate waters Iron and magnesia separate out as dusty hematite and in chloritic films. Nevertheless, the low soda content (1 24%, 1 76%) of the analysed rocks, 8776, 8768, makes it likely that soda has been lost in the process. It has also been seen that analcime is readily formed with addition of soda by the action of saline waters on glass. but the reasons for the different conditions causing the formation of one or other of these two zeolites at Taringatura are not clear. Although analcime has not been found in the North Range beds, the occurrence of pseudomorphs shows that it was formerly present in these rocks as it still is in the Upper Triassic sediments.

4. *Destruction of analcime and albitization of plagioclase*

These two metamorphic processes, observed with increasing depth of burial, are quite distinct and can proceed independently, but as one has probably facilitated the other and as their chemical effects seem to be interconnected, they will be treated together.

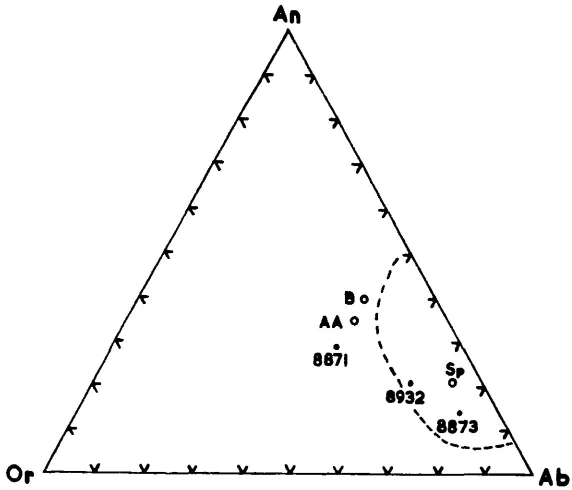
Even in the Upper Triassic analcimized tuffs, embayment of analcime by quartz and albite has already set in. The following equation shows that a simple molecular addition of silica to analcime with simultaneous loss of water approximates to a volume for volume replacement, although for this condition to be strictly fulfilled rather less silica need be added and a little Na and Al removed.

$NaAlSi_2O_6.H_2O$	$+ SiO_2$	$= NaAlSi_3O_8$	$+ H_2O$
analcime		albite	
220 1 gm., 97 9 cc.	60 gm.	262·1 gm., 100·4 cc.	

Some or perhaps all of the authigenic albite of the Upper Triassic replaces earlier-formed analcime by the addition of silica, and the fact that the analcime in these rocks is partly replaced by quartz also implies that further Na and Al must have been liberated for potential deposition in albite elsewhere It is found that when analcime is abundant in a rock, plagioclase is unalbitized or incompletely so. The soda-content of the analcime rocks is high (e.g., 6 13% in 9051) and so albitization of the plagioclase could be accomplished without any increase in the bulk soda content of the rock. Raw (1943) suggested that the early formation of analcime in palagonite tuffs from Jamaica is responsible for their soda-rich nature, and he describes how, with increasing metamorphism, albite is formed from the analcime.

With increasing temperature under hydrothermal conditions, there must be a tendency towards the break-down of lime-bearing plagioclase, but simple metamorphic break-down to albite and a lime-bearing silicate such as occurs during the early stages of regional metamorphism is not generally accompanied by any increase in the soda-content of the rocks concerned. Thus Turner (1948, p. 117) has pointed out that two greywackes from the Naseby Subdivision of North Otago contain 4·01% and 3·79% Na_2O whereas the average soda-content of twelve corresponding quartz-albite-muscovite-chlorite schists is 3 50% Na_2O. In the North Range on the other hand the albitic lithic tuff 8873 has a much higher soda-content (5·38%) and lower potash (0 92%) than the corresponding little-altered tuff 8871 (3·17% Na_2O, 2·79% K_2O).

The above mechanism of early formation of analcime by reaction between glass and saline waters, followed by destruction of the analcime and albitization of andesine at depth, seems competent to explain the soda-rich nature of many of the North Range rocks. Lime and alumina were released during the albitization of andesine-labradorite. Some of the alumina has been retained in sericite inclusions in the albite whereas the rest of the alumina and the lime have contributed to the formation of prehnite, pumpellyite, epidote, calcite, laumontite and sphene. In some cases one or more or these minerals has crystallized in place as inclusions in the albitized plagioclase, but more often their components have been cleared from the crystal under the influence of solutions enriched in soda by the destruction of analcime, and redeposited elsewhere, either interstitially in the same rock or even in a neighbouring bed. Laumontite-rich patches in the lithic tuffs and the lime-enriched laumontitized beds of vitric tuff are the result.



TEXT-FIG 3 — Normative feldspar of meta-andesitic lithic tuffs from the North Range. 8871 Little-altered andesitic tuff with fresh andesine-labradorite (NR_1). 8873 Albitized meta-andesitic tuff from the same bed as 8871. 8932 Albitic tuffaceous greywacke. (NR_5). AA Daly's average augite andesite. B Daly's average basalt Sp Average spilite of Sundius (1930). The field of the majority of spilites is indicated with a dotted line.

5. *Spilitic affinities of the albitized tuffs*

The normative feldspar compositions of the three lithic tuffs 8871, 8873 and 8932 are plotted on the Ab-An-Or diagram (Text-fig. 3), and it is seen that 8871 falls fairly near to Daly's average augite-andesite The albitized rocks fall within a field occupied by the majority of spilites plotted by Sundius (1930 p. 8) and Gilluly (1935, p. 250), and although they contain more SiO_2 and Al_2O_3 and less CaO than a typical spilite (Table III, F) they show definite spilitic (or keratophyric) affinities. Similarly the albitized meta-andesite pebbles of the North Range conglomerates could be described as keratophyres were it not that almost unaltered equivalents are found along the strike in the Hokonui Hills.

Albitization of andesite flows and associated pyroclastics to rocks of keratophyric aspect is described by Gilluly (1935) from the spilite field of Eastern Oregon. It is of interest to note, also, that a considerable series of late Palaeozoic spilites, albite dolerites, keratophyres and associated tuffs has recently been described by Reed (1950) from the West Dome peridotite belt north-north-west of Mossburn. His spilitic tuffs are not unlike the Triassic meta-andesitic tuffs of the North Range, although they appear to represent a slightly more basic magma and their metamorphism is more pronounced. An analysis of a West Dome spilite is included in Table III, together with an andesite of rather similar composition to the Taringatura tuffs, from the basement rocks of North Auckland (Bartrum, 1929).

6. *Laumontitization*

Laumontite is rare in the Upper Triassic rocks where heulandite is abundant, but in the Lower Triassic this relationship is largely reversed It is likely, although not definitely proved, that the laumontitized tuffs have passed through a heulanditized stage Certainly the laumontite rocks represent a more advanced stage in alteration, and no lime-bearing plagioclase remains in them. In at least one case an analcime-bearing tuff has later been altered to laumontite. The hypothesis that lime released during the albitization of surrounding beds of meta-andesite lithic tuffs has contributed to lime metasomatism in the laumontite rocks, has been put forward (Coombs, 1952, pp. 815-816). From the composition of the altered vitric tuffs expressed in grams per cc. (Table IV) it is seen that for equal-volume replacement, laumontitization of the heulandite rocks required addition of lime and alumina, and loss of silica and perhaps titanium, iron, manganese, magnesium and sodium.

It is instructive to consider the effects of laumontitization at equal volume, of the anorthite component of a plagioclase crystal, without change in the albite content:

$$\begin{array}{ccc} & \text{anorthite} & + \text{ water} \\ 0\ 99 & CaAl_2Si_2O_8 & + 3\ 36\ H_2O \rightarrow \\ & 276\text{ gm., } 100\text{ cc.} & 61\text{ gm.} \end{array}$$

$$\begin{array}{lllll} \text{laumontite} & + \text{ materials removed in solution.} & & & \\ 0{\cdot}42\ CaAl_2Si_4O_{12}.8H_2O & + 0\ 57\ CaO & + 0{\cdot}57\ Al_2O_3 & + 0{\cdot}30\ SiO_2 \\ 229\text{ gm , } 100\text{ cc} & 32\text{ gm.} & 58\text{ gm.} & 18\text{ gm.} \end{array}$$

Thus, even without introduction of soda into the crystal, appreciable amounts of silica and alumina and more than half the lime are released for metasomatism elsewhere and must be carried away in the interstitial solutions that provided the water for the reaction.

TABLE IV.

Composition of Metasomatized Vitric Tuffs in grams per cc.

	A	*B*	*C*	*D*	*E*
SiO_2	1.571	1.449	1.650	2.004	2.058
TiO_2	.009	.005	.010	.005	.004
Al_2O_3	338	388	388	324	.246
Fe_2O_3	025	.052	.073	.044	.042
FeO	058	013	.026	.010	014
MnO	.0015	0007	0005	.000	0004
MgO	032	007	.021	.006	.010
CaO	078	130	077	032	.012
Na_2O	037	.010	.063	136	027
K_2O	.073	061	113	.035	145
H_2O	216	260	126	035	035
P_2O_5	0025	001	.000	000	0003
CO_2	.0005	—	—	—	—
Sp. Gr.	2.44	2.38	2.55	2.63	2 59

A. Average of heulanditized tuffs, 8776, 8768
B. Laumontitized tuff, 8791.
C. Laumontitized tuff showing incipient quartz-albite-adularia metasomatism, 8800.
D Average of quartz-albite metasomatites, 8859, 8829.
E. Average of quartz-adularia metasomatites, 8819, 8817.

All the above rocks are from the North Range, Taringatura.

7 *The quartz-albite-adularia metasomatites*

Textural and mineralogical evidence prove that the quartz-feldspar-pumpellyite metasomatites replace laumontite rock, at least in part. They are the result of localized metasomatic activity of uncertain cause which occurred at a late stage in the evolution of the North Range rocks. Two albite-rich and two adularia-rich examples were chosen for analysis, but mixed types are even more abundant. The laumontite-bearing tuff, 8800, shows incipient development of quartz, albite and adularia and in many ways represents an intermediate stage in the development of these rocks as is seen in Table IV. With metasomatism there are gains in SiO_2 and Na_2O and/or K_2O, losses in Al_2O_3, CaO, H_2O and also in the minor constituents MnO and P_2O_5. It is of passing interest to note (Table V) how closely the composition of the quartz-albite rocks approaches that of certain quartz-keratophyres such as those described by Gilluly (1935, p. 235, no. 2), while the quartz-adularia rocks find chemical parallels among such rocks as the metasomatized quartz dacites of Yellowstone and the potash-enriched rhyolites of the Esterel, France (Terzaghi, 1948).

TABLE V.

Analyses of Two Quartz-albite-adularia Metasomatites and of Chemically Comparable Rocks

	A	*B*	*C*	*D*	*E*
SiO_2	73.96	75.04	77.82	78.11	77.36
TiO_2	0.24	0.10	0.17	0.08	0.32
Al_2O_3	12.99	13.39	10.03	11.50	10.73
Fe_2O_3	1.95	1.61	1.60	1.60	1.18
FeO	0 49	0.37	0.63	—	0.88
MnO	trace	0 05	0.02	—	0.04
MgO	0.40	0 18	0.40	0.25	0 42
CaO	1.97	0.40	0.25	0.51	1.09
Na_2O	5.42	6 36	0.85	0.54	1.02
K_2O	1.33	0 83	6.54	6.26	6.16
H_2O+	1.06	1.07	1.03	1.90	0.65
H_2O-	0.28	0.24	0.32	—	0.18
P_2O_5	trace	0.08	trace	—	0.06
CO_2	—	0.10	nil	—	0.50
BaO	0.02	—	0.45	—	—
	100.11	99 82	100.11	100.75	100.59

A. 8859. Quartz-albite metasomatite, NR_2 vitric tuff bed, North Range, Taringatura.
B. Quartz keratophyre, Oregon. J G. Fairchild. anal. (Gilluly, 1935, p 235, no. 2).
C. 8819. Quartz-adularia metasomatite, NR_2 vitric tuff bed, North Range, Taringatura
D Spherulitic rhyolite flow, Col des Sacs Pisani, anal. (Michel-Lévy, 1911; in Terzaghi, 1948. p. 21, no 2)
E. Thoroughly altered quartz dacite. Y.P. 325, Upper Geyser Basin core, Yellowstone, 375ft (Fenner, 1936, p. 272).

Field and textural relations plainly show that the Taringatura quartz-albite-adularia rocks have been derived from andesitic to dacitic tuffs. Isolated specimens might not have been interpreted in this way. However, if normative feldspar compositions of the potash-rich rocks 8819, 8818, were plotted on the albite-anorthite-orthoclase equilibrium diagram (e.g., Doggett, 1929, Fig. 3; Nockolds, 1946, Fig. 3) it would be found that they lie well within the orthoclase field, a field not occupied by normal late magmatic differentiates.

Terzaghi (1935, p. 379) pointed out that of the glasses with over 70% SiO_2 listed in Washington's 1917 tables, only four, all of them devitrified, fall within the orthoclase field of the Or-Ab-An equilibrium diagram. Terzaghi suggested that metasomatic enrichment in potash during alteration of glass is a common feature. Later (1948) she described a series of hydrothermally altered obsidians and spherulitic rhyolites from the Esterel in which a combination of potash metasomatism and differential leaching has brought the feldspar compositions into the orthoclase field. Some of the potash may have been introduced in hydrothermal solutions, but part was probably derived by leaching in other parts of the mass. Similarly, much of the potash deposited by thermal waters as adularia in the Yellowstone dacites and rhyolites and corresponding sands is considered by Fenner (1936, pp. 281-282) to have been derived from the leaching of lower strata. There are a number of records of adularized rocks developed among spilitic types and apparently complementary to them. Sargent (1917) found examples among the Lower Carboniferous lavas of Derbyshire and de Roever (1942, 1943) has described adularized rocks (poeneites) from amongst the albitic rocks of Timor.

At Taringatura also, there is no need to postulate an outside source for the potash of the adularized metasomatites The albitized tuffs suffered a loss of potash during their alteration and so provide an adequate source for the potash which has been concentrated into the small and highly localized adularia metasomatites.

TRACE ELEMENTS

In the hope of throwing more light on the metasomatic processes, as well as on the composition of the zeolites and feldspars, Dr. S. R. Nockolds has kindly carried out spectrographic analyses (Table VI) of the chemically analysed rocks

Two of the most interesting results are the demonstration of an appreciable content of barium in the adularized rocks, and of barium and strontium in the heulandite rocks. Thus in the adularia-rich metasomatite 8819 there are 4,000 parts per million of Ba, indicating a celsian content of 2·5% in the adularia itself. There is an analogy here with the hydrothermal barium-rich adularias of the " alpine clefts " of Switzerland. von Engelhardt (1936) pointed out that although there is a strong tendency for a fall in the barium content of potash feldspars with falling temperature during magmatic differentiation, nevertheless hydrothermal adularia is freed of these controls and often has a high barium content depending on the local composition of the solutions from which it was deposited.

Notes on individual elements follow.

Barium

The most significant facts in the distribution of barium are·

(1) a moderate barium content (500 p.p.m) in the least altered andesite tuff (8871) and a significantly lower barium content and Ba : K atomic ratio in its albitized equivalent (8873);

(2) high barium (2,000-3,000 p p.m.) and high Ba : K, Ba Ca ratios in the heulandite rocks;

(3) very low barium (10 p.p.m.) in the purer laumontite rock, 8791;

(4) an increase in the barium content and in Ba : K ratios in the mixed laumontite-metasomatic feldspar rock, 8800, reaching a very high value in the quartz-adularia rocks, one of which contains 4,000 p.p.m.

In most minerals, Ba″ (1.43 Å) can proxy more readily for K′ (1·33 Å) than for Ca″ (1 06 Å) and in the quartz-adularia rocks (8817, 8819) Ba : K = 0 01–0 02 . 1, indicating that 1–2% of the K positions are occupied by Ba.

In the heulandite rock 8776, over half the potash (2 71%) must be in the heulandite itself for the mineral carries 2·68% K_2O and makes up the greater part of the rock. The ratio Ba : K is 0·04 : 1 in this rock, a higher value than in the adularia rocks, and it is possible that the greater part of the barium is carried by the heulandite. Calcium in the two heulandite rocks is divided between heulandite, andesine and augite, the latter two being subordinate in 8768 and almost negligible in 8776. Since Ba : Ca equals 0·04 : 1 in 8776, the ratio Ba : Ca in the heulandite itself must be of the same order of magnitude.

A large number of published heulandite analyses show over 1% K_2O and some have over 3%. In contrast laumontite is essentially a lime zeolite and determinations of K_2O greater than 0·5% are rare. Replacement of Ca″ by K′ in laumontite is evidently difficult, and this being so, replacement by the even larger Ba″ ion should be still more difficult. This may explain the extraordinarily low Ba : K and Ba : Ca ratios in the rock 8791, a rock which contains about 70% of laumontite.

The andesite tuff 8871 contains accessory heulandite, and as has been seen, both the absolute value of the barium content and the ratio Ba : K drop in the albitized equivalent 8873. It is probable that most of the barium is in the heulandite and feldspar and is lost during albitization.

Strontium

The trend of strontium closely follows that of barium in all rocks except those in which appreciable secondary adularia is found. Thus the ratio Ba . Sr is steady within the range 0·2–0·6 : 1 in the lithic tuffs, heulandite rocks and the purer laumontite rock, but in the quartz-adularia rocks reaches 100 :1. Sr″ (1 27 Å) replaces Ca″, not K′ in the North Range minerals.

As was the case with barium, so with strontium is seen the extraordinary failure of entry into the laumontite structure in contrast to ready replacement of calcium by strontium in heulandite (cf. strontium-rich heulandites reported by Walker and Parsons, 1922; and Slawson, 1925). The relationship in the North Range can be shown to a first approximation as follows

Ca″ replaced by Ba″ in heulandite :— 4%
Ca″ replaced by Sr″ in heulandite .— 10%
Ca″ replaced by Ba″ in laumontite .— 0.007%
Ca″ replaced by Sr″ in laumontite :— 0.05%

In comparison it may be noted that van Tongeren (1938) has recorded a laumontite from Sumatra with 0·1% SrO, 0·02% BaO, corresponding to approximately 0·07% Ca atoms replaced by Ba, and 0 5% by Sr.

Corresponding to its moderately high barium content the andesite tuff 8871 contains a fairly high strontium content. Most of this is presumably contained in the andesine (cf. Noll, 1934; Nockolds and Mitchell, 1948; Wager and Mitchell, 1951) and in the heulandite, and the loss in strontium and drop in the ratio Sr : Ca during albitization can be correlated with the destruction of these two minerals. The relict and newly formed lime-bearing minerals, augite, calcite, epidote, etc., evidently carry a much lower total strontium content. Similarly the Sr · Ca ratio is very low (0·0003 to 0 006) in the quartz-feldspar metasomatites in which pumpellyite is the main lime-bearing mineral.

Rubidium

The ratio Rb : K is remarkably constant within the range 0 001–0 006 except in the laumontite rock 8791 in which the rubidium concentration is below the limits of sensitivity of the spectrograph. The drop in rubidium from 300 to 15 p.p.m. during albitization of the andesite tuff 8871 can be correlated with the destruction of lime-bearing plagioclase and of heulandite The concentration rises again in the quartz-adularia rocks to 200-300 p p.m corresponding to 0 3% of the K atoms in the adularia replaced by Rb.

Gallium

The atomic ratio Ga ·Al is fairly steady in the range 1 10,000–1 25,000, but is rather low in the quartz-adularia rocks. There is thus no notable concentration as has sometimes been noted in deposits from alkaline thermal waters

Zirconium and yttrium

The distribution of these elements is largely a function of heavy mineral sorting during transport and deposition of the tuffs as sediments. Thus the coarse, rather poorly-sorted vitric tuff 8800 contains more zirconium and yttrium than 8791 and 8776 which were composed of fine, well-sorted ash

Discussion

During the breakdown of detrital feldspars and heulandite, and the formation of albite and laumontite, one can picture a progressive enrichment of the interstitial solutions in potassium, barium, strontium and rubidium The last important work of these solutions was the localized quartz-albite-adularia metasomatism. Adularia was freely deposited and even replaces analcime. The barium concentration in the solutions had risen high enough for an important amount of barium to enter the adularia structure. On the other hand strontium did not enter the adularia, presumably on account of its small ionic size. Under low-temperature hydrothermal conditions the adularia structure is possibly intolerant of ions much smaller than that of K′ whereas the larger Ba″ (and rarer Rb′) can still enter fairly readily Similarly Noll (1934, p 548) reports only 0 04% SrO in adularia from St. Gotthard, whereas Niggli, Koenigsberger and Parker (1940, p. 545) found 0 48 and 0 78% BaO.

A striking feature of the trace element distribution is the high concentration of barium and strontium in the heulandite-bearing rocks, higher indeed than in most igneous rocks, although in a few of the East Indian andesites examined spectrographically by van Tongeren (1938) comparable values are attained. It may well be that the original volcanic glass from which the heulandite is derived was particularly rich in these elements, or it is just possible that they have been supplemented during the initial zeolitization. In this respect it is of interest that Sr″ is the fifth most abundant cation in sea water (Rankama and Sahama, 1950). Certainly heulanditization occurred very early in the evolutionary history of the rocks and from this stage onwards there is nothing to suggest that any members have received concentrations of any element which could not have been derived by redistribution from elsewhere in the mass.

SUMMARY OF RESULTS

1. Repeated vulcanicity is recognized in the Triassic of New Zealand. In Taringatura Survey District, Southland, andesite, dacite and rhyolite tuffs are present in large amount and at many horizons through a 28,000ft. section, interbedded with conglomerates, greywackes and indurated mudstones, mainly or entirely of marine deposition.

2. In the upper members of the Triassic succession fairly normal sedimentary diagenetic phenomena are observed, such as the formation of overgrowths on feldspars, cementation by quartz and chloritic minerals, and the replacement of volcanic glass by heulandite and analcime. These two types of zeolitization of tuffs are of regional importance in the Triassic of southern New Zealand. Heulanditization requires little chemical change except apparently a loss of soda, and in some cases a loss of silica, whereas analcimization, under the influence of saline waters, results in an increased soda content and decreased potash. A small proportion of the analcime crystallized in cross-cutting veinlets after consolidation.

3. In addition to connate waters trapped in the sediments, vast quantities of water were stored up in volcanic glass and in zeolites of early formation. As the temperature rose, perhaps to the order of 150–300° at the base of the pile, this stored-up water facilitated a special type of metamorphism, low-grade hydrothermal in its effect, although unrelated to igneous activity.

4. With increasing depth of burial, analcime gave way to quartz and feldspars, and in the lowest members it is represented only by pseudomorphs At least a part of the interstitial authigenic albite of Upper Triassic sediments has formed directly from analcime.

5. With increasing depth also, a steadily increasing proportion of detrital plagioclase was albitized This is not a simple metamorphic breakdown of lime-bearing plagioclase to albite and secondary lime-bearing minerals, although such a tendency was undoubtedly operative at the moderately elevated temperature at the base of the pile. In many cases the anorthite component was completely cleared from the crystal, apparently under the influence of soda released by the metamorphism of analcime, and the resulting pseudomorphs were purely albitic apart from sericite inclusions.

6. Albitized augite-andesite tuffs in the North Range have spilitic affinities. Their soda-rich nature may result from the early formation, and later destruction, of analcime.

7. In some cases the lime and alumina released during albitization crystallized within the same body of rock as laumontite, prehnite, pumpellyite, epidote, calcite, and sphene (by alteration of ilmenite). In other cases much of the lime was removed and concentrated elsewhere, especially in the altering beds of vitric tuff, where it was "fixed" as laumontite, which appears to replace earlier formed heulandite and even analcime. The albitized rocks also suffered a loss in potash.

8. Localized metasomatism occurred within a 450ft. bed of impure laumontitized tuff and resulted in the formation of quartz-albite-adularia-pumpellyite rocks, sometimes enriched in potash, sometimes in soda.

9. Most of the zeolitized, albitized and adularized rocks deviate from their original composition to a greater or less extent, but the metasomatism of the various masses appears to be complementary and there is no need to postulate post-diagenetic introduction of material from outside sources. This conclusion is supported by spectrographic analyses of the trace elements. Interesting points are high concentrations of barium and strontium in the heulanditized rocks, and of barium in the adularia.

Acknowledgments

Preliminary petrographic examination of many of the rocks described in this paper was made at the University of Otago under the guidance of Professors W. N. Benson, F. J. Turner and C. O. Hutton. Virtually all the detailed mineralogical and chemical work was carried out at the Department of Mineralogy and Petrology, Cambridge, while the writer held an 1851 Exhibition Science Research Scholarship. The writer gratefully acknowledges the encouragement received from Professor C. E. Tilley. To Dr. S. R. Nockolds he is indebted for the valuable set of spectrographic analyses and for discussion of many topics, to Mr. J. H. Scoon for guidance on analytical questions, to Dr. N. F. M. Henry for discussion on the interpretation of X-ray photographs and to Mr. K. Rickson for assistance with their production. Dr. J. Marwick kindly forwarded a small set of "greywackes" from other parts of New Zealand for comparative purposes and Messrs. J. D Campbell and I. C. McKellar kindly allowed the writer to examine material collected by them. Dr. D. A. Brown has assisted with critical comments on the manuscript.

Postscript.

Since this paper went to the press, an example of the North Range rocks termed " tuffaceous greywacke " on pp. 83, 85 (e.g., 8932) has been figured by Williams, H., Turner, F J., and Gilbert, C. M. (1954) in their new book *Petrography,* as fig. 99c, p 303, under the classification of " volcanic greywacke". Except in those cases where a contemporaneous pyroclastic admixture can be proved, as for example by the presence of glass shards, this name is to be preferred to the term " tuffaceous greywacke " as used on the above mentioned pages. Some of the Upper Triassic sediments such as 8952, p. 90, can also be classified appropriately as volcanic greywackes

TABLE VI.

Spectrographic Analyses

(All figures refer to parts per million. Analyses by Dr. S. R. Nockolds.)

	Ionic Radius	*Limit of Sensitivity*	*8871*	*8873*	*8932*	*8776*	*8768*	*8791*	*8800*	*8859*	*8829*	*8819*	*8817*	
Ga	0.62 Å	5	20	20	20	15	10	8	20	15	10	x	5	Ga
Cr	0.64	1	30	25	80	x	7	8	10	3	n.d.	tr. ?	n.d.	Cr
V	0.65	10	100	125	250	x	20	20	35	20	n.d.	20	n.d.	V
Li	0.78	1	60	55	35	25	45	20	30	30	30	60	80	Li
Ni	0.78	2	10	10	30	x	x	x	x	x	n.d.	x	n.d.	Ni
Co	0.82	5	20	15	30	x	x	x	x	x	n.d.	x	n.d.	Co
Sc	0.83	10	20	x	25	x	10	x	20	x	n.d.	x	n.d.	Sc
Zr	0.89	10	165	100	200	150	175	160	275	150	n.d.	175	n.d.	Zr
Cu	0.83	5	25	40	25	x	10	5	10	15	n.d.	10	n.d.	Cu
Y	1.06	15	30	30	40	x	35	35	45	35	n.d.	30	n.d.	Y
Sr	1.27	10	2,000	50	200	3,500	5,000	40	100	10	20	25	15	Sr
Pb	1.32	15	tr.	x	x	x	15	20	25	20	10	10	10	Pb
Ba	1.43	10	500	40	200	3,000	2,000	10	1,000	200	250	4,000	1,500	Ba
Rb	1.49	5	300	15	50	50	200	x	200	10	10	300	200	Rb

Be (10), Mo (5), Sn (15), In (1), La (40), Ag (1) and Tl (2) were not detected (approximate limits of sensitivity in brackets).

TABLE VII.

Important Atomic Ratios.

	8871	*8873*	*8932*	*8776*	*8768*	*8791*	*8800*	*8859*	*8829*	*8819*	*8817*
Ba/K	.006	0015	004	.04	.02	.0001	.007	.005	.006	.02	.01
Ba/Ca	.005	.0004	.002	.04	.03	.00007	.01	004	.02	.7	.1
Sr/K	.04	.003	.007	.07	.08	.0008	.001	.0004	.0008	.0002	.0002
Sr/Ca	.03	.0008	.001	.08	.1	.0005	.002	.0003	.0025	.006	.001
Ba/Sr	.2	5	.6	.5	.3	.2	7	15	9	100	70
Rb/K	.006	.001	.002	.001	.003	—	.0025	.004	.004	.003	.0025

Note.—For descriptions of specimens see opposite

TABLE VIII.

Chemical Analyses of Taringatura Rocks (Analyst D. S. Coombs)

	8871	*8873*	*8932*	*8776*	*8768*	*8791*	*8800*	*8859*	*8829*	*8819*	*8817*	*8818*	*9108*	*9051*
SiO_2	57.13	56.56	55.75	62.91	65.59	60.90	64.71	73.96	78.07	77.82	80.46			
TiO_2	1.27	1.52	1.34	0.37	0.38	0.21	0.41	0.24	0.13	0.17	0.13			
Al_2O_3	16.03	15.24	16.16	13.85	13.76	16.30	15.22	12.99	11.68	10.03	8.89			
Fe_2O_3	3.17	3.28	1.25	1.01	1.05	2.18	2 85	1.95	1.36	1.60	1.63			
FeO	5 35	5.46	7.34	2.28	2.43	0.55	1 00	0.49	0.30	0.63	0.46			
MnO	0.10	0.12	0.12	0.08	0.04	0.03	0.02	tr.	tr.	0.02	0.01			
MgO	2.51	2.60	3.87	1.42	1.18	0.28	0.82	0.40	0.04	0.40	0.39			
CaO	4.00	3.77	3.50	3.19	3.13	5.45	3.01	1.97	0.44	0.25	0.64			
Na_2O	3.17	5.38	4.39	1.24	1.76	0.42	2.45	5.42	4.89	0.85	1.21	1.41	5.10	6.13
K_2O	2.79	0.92	1.59	2.71	3.25	2.54	4.46	1.33	1.31	6.54	4.59	10.47	1.54	1 04
H_2O+	3.27	2.54	3.51	7.80	5.37	8.22	4.01	1.06	1.07	1.03	0.98			
H_2O-	0.78	0.75	0.72	2.81	1.68	2.70	0.92	0.28	0.27	0.32	0.32			
P_2O_5	0.23	0.22	0.30	0.12	0.07	0.05	tr.	tr.	tr.	tr.	0.02			
CO_2	0.09	1.37	0.44	nt.fd.	0.05	nt.fd.	nt.fd.	nt.fd.	nil	nil	nil			
BaO*	0.06	0.00	0.02	0.34	0 22	0.00	0.11	0.02	0.03	0.45	0.17			
Total	99.95	99.73	100.30	100.13	99.96	99.83	99.99	100.11	99.59	100.11	99.90			
Sp. Gr.	2.70	2.74	2.74	2.40	2.49	2.38	2.55	2.66	2.61	2.61	2.59			

* Spectrographic determinations by Dr. Nockolds.

8871. Andesine-bearing augite-andesite tuff with a little heulandite after glass. Bed NR_1, North Range, Taringatura Survey District, Southland.
8873. Albitized, meta-andesite lithic tuff. Bed NR_1.
8932. Albitic tuffaceous greywacke. Bed NR_5.
8776. Fine-grained, heulanditized vitric tuff. Bed NR_7.
8768. Coarse-grained, heulanditized vitric-crystal tuff. Bed NR_2.
8791. Fine-grained laumontitized vitric tuff. Bed NR_5.
8800. Coarse-grained laumontitized vitric-crystal tuff, with a small amount of secondary quartz and feldspars. Bed NR_2.
8859. Quartz-albite-adularia-pumpellyite metasomatite, albite-rich phase. Bed NR_2.
8829. Ditto. Albite-rich phase. Bed NR_2.
8819. Ditto. Adularia-rich phase. Bed NR_2.
8817. Ditto. Adularia-rich phase. Bed NR_2.
8818. Ditto. Concentration of adularia-rich lapilli.
9108. Analcime-rich tuffaceous greywacke, Kaihiku Gorge, Southland.
9051. Analcime-rich impure crystal-vitric tuff (Otamitan), Wether Hill, Taringatura.

TABLE IX.

Norms, Weight Per Cent.

		8871	*8873*	*8932*	*8776*	*8768*	*8791*	*8800*	*8859*	*8829*	*8819*	*8817*
Q		14.0	11.8	8.0	35.0	33.2	36.7	25.6	33.0	43.5	46.3	53.7
C		1.3	2.2	2.5	3.1	1.7	3.2	0.8	—	1.4	0.7	0.6
Or		16.6	5.5	9.4	16.1	19.3	15.1	26.4	7.9	7.8	38.8	27.2
Ce		0.1	—	0.1	0.8	0.5	—	0.2	0.1	0.1	1.0	0.4
Ab		26.5	45.6	37.2	10.5	14.9	3.6	20.6	46.0	41.4	7.2	10.3
An		17.9	8.6	12.7	15.1	14.8	26.7	14.9	7.1	2.2	1.2	3.2
	Wo	—	—	—	—	—	—	—	1.0	—	—	—
Di	En	—	—	—	—	—	—	—	1.0	—	—	—
Hy	En	6.3	6.5	9.7	3.5	2.9	0.7	2.2	0.0	0.1	1.0	1.0
	Fs	5.3	5.0	10.5	2.9	3.1	—	—	—	—	—	—
Mt		4.6	4.7	1.8	1.5	1.5	1.3	2.1	0.9	0.6	2.0	1.1
H		—	—	—	—	—	1.3	1.4	1.3	0.9	0.2	0.8
Il		2.4	2.9	2.5	0.7	0.7	0.4	0.8	0.5	0.2	0.3	0.2
Ap		0.5	0.5	0.7	0.3	0.2	0.1	—	—	—	—	0.1
Cc		0.2	3.1	1.00	—	0.1	—	—	—	—	—	—
		4.1	3.3	4.2	10.6	7.0	10.9	4.9	1.3	1.3	1.4	1.3
$H_2O\pm$		99.8	99.7	100.3	100.1	99.9	100.0	99.9	100.1	99.5	100.1	99.9

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