Sedimentary analcime rocks and sodium-rich gneisses

By D. S. Coombs

Geology Department, University of Otago

Summary. As indicated by Tilley (1925), albite-rich schists and gneisses can inherit their abnormal chemical characteristics from sediments that are proving to be by no means rare. They may be rich in detrital sodic plagioclase or they may contain authigenic analcime. Some sedimentary analcime rocks ('analcimolites') carry normative nepheline and so offer potential parent rocks for nepheline-bearing gneisses provided that, in these gneisses, $SiO_2 \geqslant (4Na_2O+6K_2O)$ in molecular proportions. The chemistry and occurrence of soda-rich sediments are reviewed. Some New Zealand occurrences are newly described and hitherto unpublished analyses are presented for porphyroblastic albite schist and felsitic volcanic arenite from Otago, and for analcime-rich sediments from four localities.

Moderately sodic metamorphic and sedimentary rocks

IN metamorphic terrains layered rocks of unusually high soda content are occasionally encountered. This chemical feature is reflected by the presence of unusually large amounts of albite or more rarely by the presence of nepheline. In table I porphyroblastic albite schist 1, from Otago (Turner and Hutton, 1941), and 2, from Antrim (Reynolds, 1942), are compared with some moderately soda-rich greywackes and related sediments (3 to 8). Two of these (3 and 4) are from the Murihiku Supergroup which forms the 20,000 to 30,000 foot Triassic–Jurassic sequence of the Southland Syncline, New Zealand. While their soda contents, 5·38 and 5·6 % respectively, are undoubtedly higher than the average for rocks of the group, the presence of 30 to 40 % detrital sodic plagioclase is not uncommon, in addition to that plagioclase contained within lithic fragments and authigenic cement. In such rocks soda contents of 4 to 6 % are to be expected. A point count of the analysed felsitic volcanic arenite (table I; 4) showed 42 % separate mineral grains (14 % quartz, 20 % albite, 8 % K-feldspar, rare magnetite, biotite, and epidote), 54 % composite fragments (25 % leucocratic volcanic rocks, 5 % andesitic, 10 % granular quartz-feldspar rocks, 14 % sedimentaries and hornfelses), and 4 % matrix and cement including 2 % calcite. It is conceivable that both the New Zealand rocks cited may, at an early stage of diagenesis, have contained minor amounts of analcime which gave way to albite under conditions of low-grade burial metamorphism in the zeolite facies. In the particular rocks concerned there is no real evidence for this, although the process has undoubtedly been operative in the Murihiku Group (Coombs, 1954 and 1961).

TABLE I. Some albite schists and moderately sodic sediments

	1*	2	3	4*	5	6	7	8
SiO_2	65·10	51·92	56·56	71·6	71·1	69·69	61·98	58·82
Al_2O_3	15·67	20·47	15·24	14·0	13·9	13·53	17·20	16·46
Fe_2O_3	0·97	1·51	3·28	1·2	tr	0·74	1·42	1·10
FeO	3·06	6·98	5·46	1·85	2·7	3·10	4·49	7·20
MnO	0·05	0·10	0·12	0·01	0·05	0·01	0·10	0·09
MgO	1·69	4·67	2·60	0·1	1·3	2·00	3·27	4·92
CaO	2·00	1·19	3·77	1·0	1·8	1·95	1·00	0·76
Na_2O	5·27	4·16	5·38	5·6	3·7	4·21	5·27	4·03
K_2O	1·59	4·70	0·92	1·95	2·3	1·71	2·04	1·60
H_2O^+	2·14	2·78	2·54	0·92	1·9	2·08	2·70	3·73
H_2O^-	0·18	0·18	0·75	0·32	0·26	0·26	0·10	0·11
TiO_2	0·75	0·63	1·52	0·25	0·50	0·40	0·60	0·73
P_2O_5	0·26	0·44	0·22	0·35	0·10	0·10	—	0·17
CO_2	1·25	tr	1·37	0·26	0·12	0·23	—	0·01
Others	0·03	0·16	—	—	0·09	—	—	0·08
	100·01	99·89	99·73	99·4	99·8	100·01	100·17	99·81

* Newly published analysis.

1. Porphyroblastic albite schist with muscovite and chlorite, O.U. 6238, South Branch, Waikouaiti River, East Otago, previously described by Turner and Hutton, 1941. Anal. F. T. Seelye.
2. Porphyroblastic albite schist, Ben Ledi beds, Co. Antrim (Reynolds, 1942). Anal. A. Gibbs.
3. Volcanic greywacke or lithic tuff 8873 with albitized plagioclase, North Range, Taringatura, New Zealand ('Hokonui facies') (Coombs, 1954). Anal. D. S. Coombs.
4. Felsitic volcanic arenite, Kaihikuan stage (Middle Triassic), Nugget Point, New Zealand, Grid Ref. S179/571017 (Prov.). Anal. N.Z. Dominion Laboratory.
5. Composite sample, average Wellington, New Zealand 'Alpine facies' greywacke. (Reed, 1957). Anal. J. A. Ritchie.
6. Average of three Franciscan greywackes, California (Taliaferro, 1943, p. 136).
7. Matrix of tillite, Cobalt series, Ontario (in Pettijohn and Bastron, 1959, p. 595, A). Anal. M. F. Cooper.
8. Varied argillite, Cobalt series, Ontario (Pettijohn and Bastron, 1959, p. 595, C). Anal. M. Balazs.

The relatively high soda content of the rocks in table I may stem from a variety of causes such as the nature of the source rocks, diagenetic processes including the formation of analcime, and possibly pervasive metasomatism during very low-grade burial metamorphism (Pettijohn and Bastron, 1959). Reciprocal metasomatic processes have locally been operative during low-grade burial metamorphism in the Southland Syncline (Coombs, 1954) where sporadic distribution of laumontite, prehnite, and pumpellyite suggests the possibility that some beds or parts of beds may have lost lime and gained soda during alteration of calcic plagioclase to albite while elsewhere lime has been concentrated and soda probably lost, along with potash and certain trace elements. Any regional introduction of material is quite dubious. In any event the sodic sediments of table I are by some standards unmetamorphosed rocks and during higher grade isochemical metamorphism they would inevitably yield albite-rich schists and gneisses. Of course during actual metamorphic processes the composition of individual laminae, segregations and perhaps larger units (e.g. Pichamuthu, 1960) may well be modified by metamorphic differentiation processes.

Referring to the albite of the schists of Cowal, Tilley (1925, p. 108) remarked: 'By its abundance it marks out a peculiar type of sediment, the interest of which is here mainly stratigraphical.' Occasional claims that there is a lack of appropriate sedimentary parent rocks for albite schists of the Cowal, Antrim, and Otago types, are invalid. Any case for a metasomatic origin for such rocks must rest either on statistically based patterns of chemical variation that transcend the remarkable inhomogeneities sometimes produced both along and across bedding by normal sedimentary and diagenetic processes, or on textural evidence (e.g. Jones, 1961), the interpretation of which is commonly beset by many difficulties. It may be commented in fact that porphyroblasts growing at the expense of smaller crystals during isochemical metamorphism might be expected to show either replacement or push-aside textural details where they impinge on neighbouring grains of other mineral species, while cross-cutting segregation veins might easily be misinterpreted as evidence of invading solutions.

Strongly sodic banded schists and gneisses

Other banded schists and gneisses have been described with still higher soda contents. Where the high soda is restricted to zones in proximity to intrusives, a suggestive case for a metasomatic origin exists, as has been claimed by Bowes (1954) for the albite schists and albite–chlorite schists of Rosetta Head, South Australia (e.g. table II; 9).

Gummer and Burr (1946) have demonstrated the essentially conformable, banded nature of the nepheline-bearing gneisses of the Bancroft area, Ontario, and have given field and petrographic evidence for the belief that they result from metasomatic replacement of calcareous rocks of the Grenville. Tilley (1958) has recently described the sequence of nepheline-bearing gneisses, over 500 feet thick, intercalated in Grenville marbles at York River, east of Bancroft, Ontario (e.g. table II; 10–13), and he has cited strong textural evidence that replacement has a place in the evolution of the belt.

TABLE II. Some high-soda schists and gneisses

	9	10	11	12	13	14	15
SiO_2	58·91	51·92	49·59	45·42	42·85	65·89	70·40
Al_2O_3	21·37	20·27	23·32	25·60	24·17	20·53	16·44
Fe_2O_3	0·82	0·26	1·44	0·55	0·73	0·29	0·84
FeO	1·90	6·56	4·32	7·16	7·69	0·22	0·40
MnO	0·03	0·20	0·11	0·18	0·21	abs	abs
MgO	4·50	0·45	1·18	0·27	0·59	0·65	1·53
CaO	0·78	6·28	5·68	4·75	7·13	0·43	0·45
Na_2O	8·72	6·70	9·92	8·15	7·35	9·88	7·56
K_2O	0·16	2·44	2·35	4·04	3·89	1·06	1·10
H_2O^+	1·47	0·93	0·72	1·53	1·36	0·53	0·45
H_2O^-	0·06	0·05	0·03	0·04	0·10		0·04
TiO_2	0·85	0·27	0·47	0·30	0·30	0·39	1·16
P_2O_5	0·21	0·13	0·38	0·02	0·23	0·13	0·13
CO_2	—	3·31	0·59	1·95	3·41	abs	abs
Others	0·21	(0·06)	—	—	—	—	—
	99·99	99·83	100·10	99·96	100·01	100·00	100·50

9. Albite schist with chlorite. Rosetta Head, Encounter Bay, South Australia (Bowes, 1954). Anal. D. R. Bowes.
10. Biotite–oligoclase gneiss with calcite, Egan Chute, York River, Ontario (Tilley, 1958; table III, no. 3). Anal. J. H. Scoon.
11. Hornblende–nepheline–albite gneiss, drill-core Y.R. 10 (124 feet) York River, Ontario (Tilley, 1958; table VI, no. 2). Anal. J. H. Scoon.
12. Biotite–nepheline–plagioclase gneiss, west bank of York River at Egan Chute, Ontario (Tilley, 1958; table II, no. 1). Anal. J. H. Scoon.
13. Biotite–plagioclase–nepheline gneiss with calcite, drill core Y.R. 10 (198 feet), York River, Ontario (Tilley, 1958; table IV, no. 3). Anal. J. H. Scoon.
14. Average of three banded albite rocks, Broken Hill, N.S.W. (Vernon, 1961, p. 50). Anal. P. J. J. Sinnott.
15. Banded albite rock rich in quartz, Broken Hill, N.S.W. (Vernon, 1961, p. 13, no. 4). Anal. P. J. J. Sinnott.

Banded albite and quartz-albite rocks upwards of 100 feet thick occur near Broken Hill, New South Wales (Table II; 14, 15). Vernon (1961) shows that soda contents reach 11 %, while a rock (Table II; 15) containing 7·56 % Na_2O may approximate the composition of the formation as a whole. In contrast to Condon (1959) and after extensive chemical and mineralogical study, Vernon favours an origin by selective soda metasomatism, largely on the grounds of the supposed lack of sediments of corresponding composition.

In the light of rapidly increasing knowledge of the chemistry of zeolitic sediments it is timely to re-examine this assumption as it applies to soda-rich metamorphics generally. Engel and Engel (1953) have already suggested the possibility that sedimentary analcime or clinoptilolite beds might be parents to gneisses of relatively high Na/K ratios. Many examples of zeolite beds are listed by Deffeyes (1959) and others have been reported since (in the case of analcime, e.g. McKie, 1958; Vanderstappen and Verbeek, 1959; Gulbrandsen and Cressman, 1960; Teruggi, 1962; Hay, 1963; Hay and Moiola, 1963; Moiola and Hay, 1963; Wilkinson and Whetten, in press). Examples of analcime-rich sediments for which chemical data are available will now be reviewed.

Important occurrences of sedimentary analcime rocks

Green River Formation, Wyoming, Utah, and Colorado. Bradley (1929, 1931) first described the occurrence of analcime (table III; 16, 17) in the organic dolomitic marlstones and oil shales of the Eocene Green River Formation and he demonstrated that the analcime commonly results from alteration of ash in saline waters. According to Milton *et al.* (1960), analcime is by far the most widespread of the authigenic silicates of the Green River Formation, occurring in many beds up to several feet thick, in lenses and disseminations in oil shale and volcanic sandstones. It may be commented that the Tower sandstone lentil, shown by Bradley (1959) to be a crystal tuff, and which attains a thickness of several hundred feet, is often extremely rich in authigenic analcime. The Wilkins Peak member (900 feet) is notable for its oil shales and occurrences of alkali carbonate minerals, including shortite and thick beds of trona. A new analysis of a two-inch analcime bed from this member is given in table III, column 18. In hand specimen the bed appears to be a rather friable fine-grained sandstone. The dominant constituent is inclusion-studded icositetrahedral analcime associated with fine-grained quartz, traces of carbonates and feldspars, and various accessory minerals.

Popo Agie member, Western Wyoming. Keller (1952, 1953) has shown that the Popo Agie member of the Chugwater Formation (Triassic) and its correlatives consist of up to 60 feet of more or less pure analcime, extending over some thousands of square miles in Wyoming and Utah. The analcime bed occurs among shales, sandstone, and some dolomite. Keller believes that the analcime has been formed by reaction of clay minerals rather than ash with sodium-rich lake waters. An analysis (Keller, 1952, and table III; 19) of the coarse 'oolitic' part of a specimen from Maverick Springs shows 3·47 % K_2O, 8·24 % Na_2O. While it may reflect a local concentration of potassic phases, the high potash is not reproduced in an analysis by Miss X. K. Williams of a slightly dolomitic and quartz-bearing specimen (table III; 20) from the same locality.

Yavapai County, Arizona. Ross (1928, 1941) has described analcime rock resembling a fine-grained friable sandstone occurring among Quaternary lake beds or playa deposits in western Yavapai County, Arizona. Dominant analcime is accompanied by minor quartz, feldspar, and augite and by films of nontronite. A new analysis of the rock (table III; 21) is close to analyses given by Ross of analcime concentrates from the same locality.

Lockatong argillite, New Jersey. The Upper Triassic Lockatong Formation of the Newark Group consists of a maximum of 3,800 feet of 'argillite' with subordinate beds of carbonaceous shale and siltstone. Van Houten (1960) has reported that the 'argillite' consists of variable proportions of analcime, dolomite, and feldspar with lesser amounts of illite, normally without free silica. A partial analysis (table III; 22) indicates the strongly alkaline nature of the rock. The Lockatong Formation is the thickest sediment persistently rich in analcime so far described and chemical data on its various phases will be of considerable interest.

Analcimolites of Karafou, Central Sahara, and of the Congo Basin. Joulia *et al.* (1959) have shown that one or two beds of 'analcimolite', in all 20 to 30 metres thick, occur in Lower Cretaceous continental grits of the Central Sahara and have an outcrop length of about 280 km. Associated minerals are hematite, quartz, goethite, illite, montmorillonite, kaolinite, and carbonates. The authors give fifteen chemical analyses of which three are evidently of analcime-poor rocks. The other twelve have an average of 8·31 % Na_2O (table III; 23), with a maximum of 11·00 % (table III; 24).

Vanderstappen and Verbeek (1959) and Lepersonne (1960) have described even more extensive occurrences from the Congo Basin. Here analcimolites occur as many beds, some reaching thicknesses of several tens of metres and aggregating hundreds of metres in thickness. They are interbedded with continental grits and argillites of Upper Jurassic and Lower Cretaceous Age, the whole succession totalling 700–800 metres and extending across a distance of 400 km. Desiccation

TABLE III. Chemical analyses of analcime-rich sediments

	16	17	*18	19	*20	*21	22	23	24	25	26	27	*28
SiO_2	52·48	26·51	62·6	56·07	52·1	59·3	47·37	55·37	49·00	66·56	50·04	73·20	70·4
Al_2O_3	15·78	5·19	16·4	19·34	18·7	18·3	—	18·61	21·63	15·77	17·25	13·10	14·2
Fe_2O_3	4·54	2·56	0·8	3·58	1·2	1·7	6·91	5·87	6·80	0·91	10·36	0·37	1·7
FeO			0·1	—	1·5	0·4		—	—	0·28	2·33	0·36	0·8
MnO	—	—	< 0·01	—	< 0·01	0·01	—	—	—	0·04	0·05	0·004	<0·01
MgO	0·63	6·77	0·2	0·36	1·94	0·34	—	0·52	0·39	0·28	1·59	0·38	0·5
CaO	0·36	13·50	0·4	0·64	3·10	0·20	—	1·15	1·25	1·36	1·44	0·30	0·6
Na_2O	8·63	2·36	9·3	8·24	7·57	9·90	7·11	8·31	11·00	4·87	6·94	6·20	5·7
K_2O	1·16	1·55	2·2	3·47	0·66	1·08	3·08	0·80	0·25	4·26	0·54	0·88	1·6
H_2O^+	8·96	†22·17	7·0	†7·50	8·6	8·7	—	7·07	7·97	†4·45	†6·65	5·0	4·0
H_2O^-	0·05	0·22					—	0·65	0·30	0·27	0·97		
TiO_2	—	0·20	0·02	0·49	0·95	0·18	—	1·02	1·20	0·11	0·30	0·14	0·3
P_2O_5	—	0·02	0·03	0·10	0·49	0·12	—	0·38	0·39	—	0·06	0·03	0·07
CO_2	0·29	18·27	0·6	0·18	3·22	—	—	—	—	—	1·33	0·06	—
FeS_2, S	2·74	0·86(S)	—	—	—	—	—	—	—	—	—	—	—
Bituminous matter, C	3·93	—	0·3(C)	—	—	—	—	—	—	—	—	—	—
F	—	—	—	—	—	—	—	—	—	0·60	0·16	—	—
	'99·61'	100·18	99·9	99·97	100·0	100·2	—	99·75	100·18	'100·21'	100·01	100·02	99·9
Less O for F										0·22	0·07		
										'99·99'	99·94		

* Newly published analysis. † Loss on ignition, less CO_2

fractures and lack of evidence of volcanism help support a primary sedimentary origin.

Tupungato Oil Field, Argentina. In spite of the lack of chemical data, this occurrence is worth noting. According to Baldwin (1944) the oil-bearing Dark Victor Formation of Triassic age approximately 300 metres thick consists largely of hard volcanic tuffs or 'sandstones' altered to crystals of analcime, with interbedded shales.

U.S.S.R. Sediments rich in analcime and other zeolites are extremely widespread in rocks of diverse age in the U.S.S.R. Notable occurrences include coal measures of the Kutai–Gelat district of Western Georgia (Dzotsenidze and Skhirtladze, 1953) where a thick horizon carries about 9 % Na_2O resulting from the presence of 80 to 90 % analcime together with halloysite, limonite, and coaly material. In Tuva (Bur'yanova, 1954, 1960) chemogenic analcime rocks occur, as well as thinly bedded units reaching 100 metres or more in thickness in which analcime-cemented tuffs and tuffaceous sandstones alternate with polymict sandstones. An example from the Enisei (Yenisey) River with 4·87 % Na_2O, 4·26 % K_2O (table III; 25) contains analcime icositetrahedra in a

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Legend to Table III

16. Analcime-rich, asphalt-saturated ash bed, Green River Formation, White River, Uintah County, Utah (Bradley, 1929). Anal. J. G. Fairchild.
17. Analcime-bearing oil shale, Green River Formation, Garfield County, Colorado (Bradley, 1931). Anal. J. G. Fairchild.
18. Analcime bed in oil shale (O.U. 18,593), Stauffers drill hole SBI 16,700 feet, Wilkins Peak member, Green River Formation. Analysis compiled and in part averaged from partial analyses by X. K. Williams and W. Kitt.
19. Coarse oolitic analcime rock, Popo Agie member, Maverick Springs, Wyoming (Keller, 1952). Anal. Bruce Williams Lab.
20. 'Oolitic' analcime rock (O.U. 18,570), Popo Agie member, Maverick Springs, Wyoming. Anal. X. K. Williams.
21. Sedimentary analcime rock (O.U. 18,574), Western Yavapai County, Arizona. Anal. X. K. Williams.
22. 'Normal argillite' (analcime–dolomite–feldspar–illite rock), Lockatong Formation, New Jersey (Van Houten, 1960).
23. Average of twelve analcimolites of Karafou ($Na_2O > 4$ %), Central Sahara (Joulia *et al.*, 1959).
24. Analcimolite of Karafou, no. 467, Central Sahara (Joulia *et al.*, 1959).
25. Analcime rock with potassic, cryptocrystalline matrix, Enisei River, Tuva (Bur'yanova, 1954; 1960). Anal. V. M. Koviazina.
26. Analcime rock, Tapsa River, Tuva (Bur'yanova, 1960). Anal. V. M. Koviazina.
27. Analcime chert, altered tuff in Twin Creek limestone, Preuss Creek, Idaho (Gulbrandsen and Cressman, 1960). Anal. S. D. Botts, M. D. Mack, and H. H. Thomas.
28. Analcime-rich impure crystal-vitric tuff (O.U. 18,615), Otamitan stage, Wether Hill, Taringatura, N.Z. (Grid Ref. S160/303734 Prov.)

cryptocrystalline potassic base, while a specimen from the Tapsa River (table III; 26) has 6·94 % Na_2O and 12·69 % iron oxides.

Twin Peak Limestone, Idaho–Wyoming. With the exception of some of the Russian occurrences (e.g. Kolbin and Pimburgskaya, 1955), the above occurrences appear to be confined to deposits of continental basins although Müller (1961) has recently reported alteration of ash to analcime in sea water in the Bay of Naples. The critical conditions for this reaction, evidently uncommon in ocean waters at the present day, have yet to be defined. Gulbrandsen and Cressman (1960) have recently described a 5-feet thick horizon of tuff altered to analcime chert in the marine Twin Creek limestone occurring over an area of more than 1000 square miles of Idaho and Wyoming (table III; 27). At one locality the usual assemblage of analcime, cryptocrystalline quartz, and minor albite and calcite gives way to an albite rock, perhaps the result of slightly more elevated temperatures during burial metamorphism. Gulbrandsen and Cressman favour the view that volcanic glass has reacted with sea water to give the analcime.

Murihiku Group, New Zealand. Although it is not a dominant mineral in the marine rocks of the Murihiku Group in the Southland Syncline, analcime is widespread as a cement and alteration product of glass. In the Taringatura district, analcime is confined to the upper part of the 28 000-foot section, it being represented in the lower part by pseudomorphs only. It is believed that the analcime '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' (Coombs, 1954, p. 79). The smaller amounts of analcime that occasionally incipiently replace detrital plagioclase (Coombs *et al.*, 1959) may have formed during zeolite facies burial metamorphism. Partial analyses of an analcime-bearing crystal-vitric tuff from Taringatura and of an analcime-bearing tuffaceous greywacke from Kaihiku Gorge show 6·13 % Na_2O, 1·04 % K_2O and 5·10 % Na_2O, 1·54 % K_2O respectively (Coombs, 1954, p. 105). A more complete analysis (table III; 28) is now available of a specimen from the lower portion of a 14-feet bed of an impure, sandy tuff from Taringatura. The rock contains detrital quartz, albitic plagioclase, andesitic and other rock fragments, and pumiceous ash fragments up to 3 mm in diameter. Some patches of glass have altered to celadonite and ferruginous clay minerals, but most has been replaced by anhedral analcime which also forms a cement in which it is occasionally subhedral. Local replacement by finely twinned authigenic albite, sometimes associated with secondary sphene, suggests that these rocks were once exposed to conditions near those critical for the reaction analcime plus quartz gives albite plus water, and indicates disequilibrium. It supports the view that bedded albite rocks occasionally found in the Murihiku Group, often with relict ash texture preserved, may have passed through an analcime stage.

Among the 5000–6000 feet of Middle Triassic marine siltstones, minor sandstones, and bentonitic interbeds that occur near Kaka Point on the south-east Otago coast, analcime occurs in two main ways. In various tuffaceous volcanic sandstones and crystal-vitric tuffs it occurs much as in Taringatura and is often associated with celadonite. It also occurs in bedded analcime cherts, in some respects reminiscent of those described by Cressman and Gulbrandsen. In the Tilson Siltstone on the north-west side of Kaka Point itself conspicuously pale-olive-weathering analcime cherts appear in three main zones respectively about 80, 375, and 440 feet below the top, and aggregating about 40 feet in thickness. In thin sections fine vitroclastic texture is sometimes clear, sometimes obscure. As well as analcime and cryptocrystalline quartz, subordinate finely twinned authigenic albite is usually present and sometimes a cryptocrystalline heulandite mineral and montmorillonite. By increase in the proportions of heulandite ($n = 1{\cdot}495 \pm 0{\cdot}005$) and montmorillonite, units of analcime chert, a few inches or feet thick, pass rapidly both along and across the bedding into bentonitic or silty heulandite–montmorillonite rocks containing subordinate quartz and fine vitroclastic texture. Thus a thick and apparently homogeneous analcime chert may be represented a few feet along strike by interbedded analcime cherts and heulandite bentonites. Finely crystalline analcime occurs in joints and occasional minor fault planes. About 50 feet of the Bates Siltstone on the south-east side of Kaka Point are made up of similar rocks in about eight main horizons, and others occur in the Potiki Siltstone underlying the Bates. The field relations suggest that in these cases alteration of the ash occurred after burial, rather than at a sediment–sea water interface. The bulk composition of the two contrasted assemblages analcime–quartz(–albite) and heulandite–montmorillonite–quartz may well be closer to the parent ash than is either of the separate assemblages.

Discussion

The analyses of analcime-rich sediments in table III and of less strongly sodic sediments in table I show between them a wide range of features reflecting mainly varying proportions of analcime, quartz, detrital and authigenic feldspars, various clay minerals, oxides, and carbonates. Thus SiO_2 ranges from 26·51 % to 73·20 % and iron oxides from 0·9 % to 12·7 %. In an analysed dolomitic example the ratio $FeO+Fe_2O_3/MgO$ is 2·56/6·77 whereas in non-dolomitic cases it reaches 12·69/1·59 and 3·05/0·1. Potash may be insignificant or may approximate in amount to soda. Lime values vary widely, primarily with calcite and dolomite and to a less extent with detrital plagioclase. Where magnesium is present mainly in dolomite, as in many of the continental lake bed zeolitites, the ratio MgO/CaO is rather low. However, where magnesium-rich clay minerals are more abundant relatively high MgO/CaO ratios may be achieved. There is a tendency in this direction in the greywackes of table I and more especially in the rocks of the Cobalt series, Ontario (I; 7, 8), as discussed by Pettijohn and Bastron (1959). These are sufficiently close to the albite schist of County Antrim (I; 2) and the albite–chlorite schist from Rosetta Head, South Australia (II; 9) to lend support to the earlier conclusion that the chemistry of the latter rocks is not incompatible with the composition of sedimentary rocks. The Otago porphyroblastic albite schist (I; 1) presumably was derived from a volcanic greywacke or volcanic sandstone either with a rather high detrital albite content or with a moderate amount of authigenic analcime. The banded albite rocks of Broken Hill (II; 14, 15) prove to be chemically analogous to analcime rock such as (III; 18) from Green River. Even the York River biotite oligoclase gneiss (II; 10) has chemical similarities with the partial analysis of Lockatong argillite (III; 22) and to the average Sahara analcimolite (III; 23), the main differences in the latter case lying in the carbonate content and the different oxidation state of the iron.

Sedimentary analcimes tend to be rich in silica but vary from almost the 'ideal' NaAl:Si ratio of 1:2 (Whetten and Coombs, in preparation) to about 1:2·7 (Saha, 1959). Unless there is sufficient additional silica in the sediment to raise this ratio to that of albite (1:3), as well as to satisfy the requirements of any metamorphic decarbonation reactions, nepheline is likely to appear in a metamorphic derivative rock. The potential ratio of nepheline to albite in a metamorphosed analcimolite can presumably be raised by reactions of the type:

$$\underset{\text{(in analcime}_{\text{ss}}\text{)}}{NaAlSi_3O_8}+\underset{\text{carbonates}}{CaMg(CO_3)_2} \rightarrow \underset{\text{calc silicates}}{CaMgSi_2O_6}+\underset{\text{nepheline}}{NaAlSiO_4}+2CO_2$$

Norms (table IV) calculated for some of the soda-rich rocks listed above help to illustrate the problem. The substantial water contents shown for the sediments would of course largely be lost during metamorphism together with such material as is removed in solution. On a water-free basis, the Sahara analcimolite (24) contains approximately 23% normative Ne and 59% Ab, or slightly more Ne if the iron is partly in the ferrous state. Normative nepheline occurs in some of the other Sahara analcimolites listed by Joulia *et al.* (1959), in the Green River analysis (16), Popo Agie (19), Yavapai (21), and Lockatong argillite (22).

If it is assumed, in accordance with present data, that sedimentary analcimes are never less siliceous than $NaAlSi_2O_6{\cdot}H_2O$, it follows that in a sedimentary rock containing quartz, albite, analcime, heulandite, orthoclase, muscovite, clay minerals, normal mafic minerals, carbonates, and oxides, the ratio in molecular proportions of $SiO_2/(4Na_2O+6K_2O)$ is equal to or greater than unity. For this ratio to be less than one, saline minerals such as the alkali carbonates trona or shortite of the Green River Formation must be present. More dubiously the effect could be obtained by undersaturated zeolites such as phillipsite. In the York River biotite–oligoclase gneiss (table IV; 10) this ratio is 1·47, but in the nepheline-rich gneisses (11–13) it is 1·06, 0·96, 0·99 respectively. In the analcime-rich sediments 16 and 18–24, it ranges from 1·12 to 1·63. Hence, while on purely chemical grounds it may be concluded that the biotite–oligoclase gneiss could have been derived from a soda-rich sediment, this is barely possible for the nepheline-rich gneiss 11, and impossible for 12 and 13 unless saline minerals were present. The case for a metasomatic origin for these York River gneisses (Tilley, 1958), is thus fortified.

From the above review it is concluded that with the exception of the more nepheline-rich gneisses, the analyses cited of soda-rich metamorphics and of analcime-rich sediments indicate a generally similar range of variability, though marine examples so far analysed are not as sodic as many continental analcime rocks. Lack of isochemical unmetamorphosed parent rocks for soda-rich gneisses can be assumed no longer. Furthermore, sedimentary analcime rocks occur with sufficient frequency, in sufficient bulk and in rocks of sufficiently widely varying age and tectonic environment, to make it probable that their analogues must be represented in some metamorphic terrains. Even under conditions of mild burial metamorphism zeolitized tuffs have demonstrably given way to bedded albite-rocks. Under more severe metamorphic conditions albite-rich and even nepheline-bearing schists and gneisses are to be expected.

TABLE IV. Norms and molecular proportions $SiO_2/(4Na_2O+6K_2O)$ for some soda-rich rocks listed in tables I–III

Norm of analysis	1	4	5	10	11	12	13	14	16	19	20	21	22	23	24	28
Qz	24·0	30·1	34·0	—	—	—	—	2·8	—	—	4·3	—	—	1·8	—	29·3
C	5·1	2·3	2·8	—	—	3·8	3·4	2·7	0·3	1·5	5·5	0·8		2·9	1·9	2·2
Or	9·4	11·5	13·6	14·4	13·9	23·9	23·0	6·3	6·9	20·5	3·9	6·4	18·2	4·7	1·5	9·5
Ab	44·6	47·4	31·3	49·1	23·3	13·7	10·6	83·6	67·3	56·6	64·0	77·7	47·6*	70·3	54·2	48·3
An	0·5	1·0	6·8	9·4	12·2	11·1	12·3	1·3	—	1·4	—	0·3		3·2	3·6	2·5
Ne	—	—	—	4·1	32·9	29·9	27·9	—	3·1	7·1	—	3·3	6·8*	—	21·1	—
Di	—	—	—	3·2	8·3	—	—	—	—	—	—	—		—	—	—
Hy	7·8	2·3	7·5	—	—	—	—	1·6	—	—	2·0	—		1·3	—	1·2
Ol	—	—	—	9·9	3·7	10·2	11·4	—	1·1	0·6	—	0·6		—	0·7	—
Mt	1·4	1·7	—	0·4	2·1	0·8	1·1	—	—	—	1·7	0·8		—	—	1·7
Il	1·4	0·5	1·0	0·5	0·9	0·6	0·6	0·5	—	—	1·8	0·3		—	—	0·6
He	—	—	—	—	—	—	—	0·3	4·5	3·6	—	1·1		5·9	6·8	0·5
Ru	—	—	—	—	—	—	—	0·1	—	0·5	—	—		1·0	1·2	—
Cc	2·8	0·6	0·6	7·5	1·3	4·4	7·8	—	0·7	0·4	7·0†	—		—	—	—
Others	0·6	0·8	0·3	0·4	0·8	0·0	0·5	0·3	6·6	0·2	1·1	0·2		0·9	0·9	0·2
Water	2·3	1·3	2·2	1·0	0·8	1·6	1·5	0·5	9·0	7·5	8·6	8·7		7·7	8·3	4·0
Molecular ratio $\frac{SiO_2}{(4Na_2O+6K_2O)}$	2·45	2·45	3·07	1·47	1·06	0·96	0·99	1·55	1·38	1·24	1·63	1·39	1·20	1·57	1·12	2·49

* Maximum value for Ab and minimum value for Ne calculated from partial analysis. For any SiO_2 combined with Ca, Mg, or Fe, Ne is increased and Ab reduced.

† Includes $MgCO_3$, 2·6 %.

In the case of the admittedly unusual Green River Formation further possibilities arise. It will be recalled that here, interbedded with the vast dolomitic shales, are thick and extensive trona beds. Upon conditions of ultrametamorphism these might be expected to yield a relatively low-melting alkali carbonate liquid, capable, by reaction with silicate rocks, of yielding strongly undersaturated derivative rocks. A fascinating series of reactions could be envisaged during the metamorphism and differential fusion of a sedimentary sequence of carbonates, zeolite rocks and saline beds.

It is not maintained that any of the soda-rich schists and gneisses specifically mentioned in this paper are necessarily of non-metasomatic origin. It does appear to be established, however, that sedimentary rocks which have a generally similar range of composition do in fact exist, and that an essentially isochemical metamorphic origin for soda-rich gneisses must be considered as a serious theoretical possibility.

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