The Delaney Dome Formation, Connemara, W. Ireland, and the geochemical distinction of ortho- and para-quartzofeldspathic rocks

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ABSTRACT. A number of geochemical plots are suggested by means of which metamorphosed quartzofeldspathic sedimentary rocks (meta-sandstones, meta-arkoses, quartzites, etc.) can be distinguished from their metamorphosed igneous mineralogical analogues (meta-rhyolite, meta-granite, etc.). These plots are applied to an enigmatic, partly mylonitized, quartzofeldspathic series, the Delaney Dome Formation, which is involved in a major thrust zone. The formation is shown to be igneous and is probably a meta-rhyolite. The plots proposed should have general application in identifying the precursors of both high-grade and low-grade quartzofeldspathic rocks of unknown origin.

KEYWORDS: meta-rhyolite, quartzofeldspathic rocks, Delaney Dome Formation, Ireland.

THE Dalradian rocks of Connemara, Co. Galway, Western Ireland (the Connemara Schists), are remarkable for lying nearly 50 km south of the main outcrop of Dalradian rocks which extends from Scotland to north Mayo and Donegal in Ireland. The Connemara Schists are allochthonous, having moved southwards on a major thrust plane, the Mannin thrust, which has been described by Leake et al. (1983, 1984). This thrust is only exposed around a domal structure, the Delaney Dome, in the southwest part of Connemara, south of Clifden (fig. 1). Immediately above the thrust lie metagabbros which have been recrystallized to finely lineated and foliated albite–epidote amphibolites, the Ballyconneely amphibolites. Above these amphibolites lie strongly foliated and partly sheared metagabbro and quartz diorite gneiss containing metagabbroic lumps, and above these rocks lie the Connemara Schists (Leake, 1986).

Below the Mannin thrust is a flat-lying, mono-tonous, mylonitic, and dynamically recrystallized series of quartzofeldspathic rocks called the Delaney Dome Formation (Leake et al., 1981; Leake, 1986). These rocks, which occupy less than 25 km² and have a maximum elevation of only 44 m, are the only visible exposure of the foreland on to which the Dalradian massif of Connemara was thrust. Because of the complex nature of the Highland Boundary Fault in Scotland and Ireland, and the limited outcrop and complexity of the Highland Border rocks, the nature of the Delaney Dome Formation is of considerable importance in any Caledonide synthesis of the British Isles.

This paper is concerned with identifying the origin of these quartzofeldspathic rocks and using them to develop geochemical methods which may be applied to the identification of other metamorphosed quartzofeldspathic rocks of uncertain origin. Thus, in both high-grade metamorphic terranes and in sheared and mylonitized low-temperature metamorphic sequences, rocks essentially composed of quartz and feldspar can originate as sediments (e.g. sandstones or arkoses), as acid volcanic rocks (e.g. rhyolites), as acid plutonic rocks (e.g. granitoids), as high-grade granite gneisses, migmatitic gneisses, or metasomatic rocks. Often relic textures and structures (e.g. cross-bedding) reveal conclusively the origin of a rock but this is not always so, and in such instances geochemistry may be useful.

Delaney Dome Formation

This formation is made of very fine-grained (0.05–0.1 mm) granular rocks composed of quartz
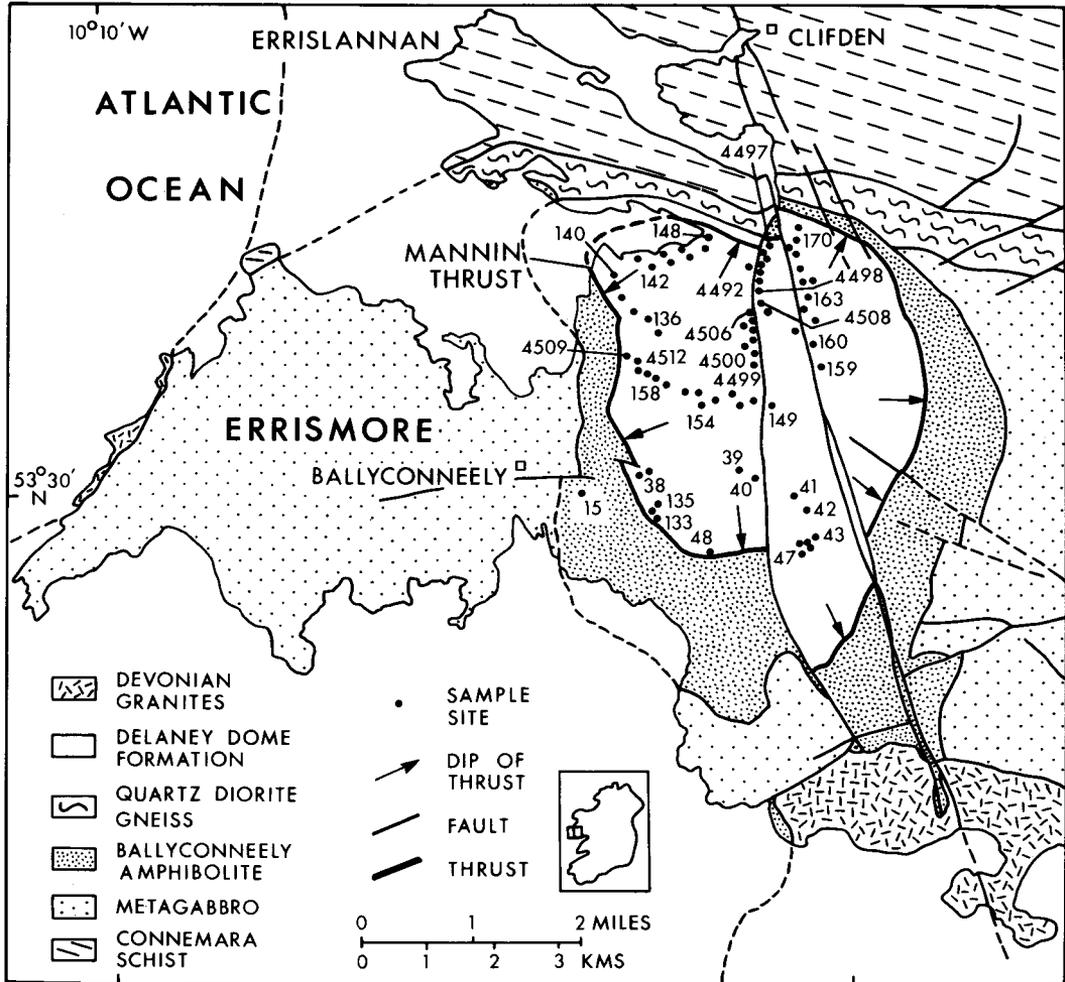
FIG. 1. Geological sketch map showing the location of the Delaney Dome Formation in the west of Ireland. The locations of the analysed samples and the sample numbers are indicated. The un-numbered points can be interpolated in the number sequence.

(60–70%), K feldspar (10–20%), plagioclase (10%), muscovite plus chlorite (5%) with accessory magnetite, epidote, and sulphides and traces of late carbonate in a few samples. Very rarely partially chloritized garnet porphyroblasts occur. In the field the rocks are pinkish, pinkish grey or grey, usually unbanded but possessing a strong foliation with parallel schistosity, lensoid quartz and penetrative shear surfaces which possess a NNW–SSE quartz stretching lineation on the foliation. Nowhere is any bedding or clear traces of original banding predating the shearing visible. Some rocks are almost mylonites with a porcellaneous or chert-like appearance; a few have muscovite–chlorite-rich

layers or sometimes green biotite, and occasionally some have magnetite-rich layers or euhedral K feldspar and plagioclase crystals in a fine-grained quartz matrix. Some of the chlorite may be altered biotite but probably most of the chlorite is of primary crystallization. The pinkish layers are not necessarily richest in K feldspar and some pink quartz is present. Often the feldspars are completely sericitized and saussuritized. The coarser quartz grains are strained and possess undulose extinction while the matrix is composed of strain-free dynamically recrystallized quartz. Thin quartz veins (0.05–0.25 mm) parallel the foliation and contain polycrystalline strained quartz porphyroclasts with

the chlorite, muscovite, and sometimes epidote fabric bowing around the quartz. From probe analyses of the rare euhedral feldspars the K feldspar is mostly orthoclase Or_{80-97} (not microcline) while the plagioclase is An_{0-20} and has Carlsbad and albite twinning.

It is not immediately obvious, whether, before the thrusting, the formation was an arkose or sandstone with recrystallized feldspar, a rhyolitic volcanic rock or glass with feldspar phenocrysts, or a granite or K feldspar granite gneiss such as occur commonly in the quartz diorite gneiss suite of Connemara. There are no exact matching rocks to the Delaney Dome Formation known in the west of Ireland. The exposed vertical thickness of the formation is difficult to calculate but is probably not more than 25 to 40 m. An undescribed borehole (Geol. Surv. Ireland 83/8) near the centre of the Dome has penetrated to 233 m nearly vertically through rocks essentially similar to those at the surface (M. D. Max and C. B. Long, pers. comm.).

Within the formation occur massive to poorly schistose uniform amphibolites made of hornblende and highly saussuritized and sericitized plagioclase. Chemically these metabasic rocks are quite different from the Ballyconneely amphibolites, having much higher $Mg/(Mg+Fe)$ ratios (typically $c.0.65$) compared with less than 0.60 for most samples of Ballyconneely amphibolite (Leake, 1986). It is clear that the amphibolites in the Delaney Dome Formation are metamorphosed intrusive or extrusive basic igneous rocks but it is not known which of these two possibilities is correct. These rocks do not throw light on the origin of the Delaney Dome Formation.

Geochemistry

Chemical analyses of twenty-nine constituents in seventy-four samples have been completed of which a representative fifty-nine samples are listed in Table I* with the sample localities given in fig. 1. The chemical analyses are by XRF using fused beads (Harvey *et al.*, 1973) for major elements and pressed powders bonded with bakelite resin for trace elements (Leake *et al.*, 1968); FeO, H_2O, and CO_2 were determined by wet chemical techniques. All the analyses were carried out by D. Singh.

The results show a range in SiO_2 from about 69 to 81 wt. % with three samples having rather lower values (overall average 73.64%). The total $SiO_2 + Al_2O_3$ is nearly always between 80 and 90 wt. % with a little over half the samples having $Na_2O >$ K_2O although the average Na_2O (3.19%) is lower

* The average analysis is the mean of all seventy-four samples.

than the average K_2O (3.45%). The significant contents of Al_2O_3 (9–14; average 12.01%) and $Na_2O + K_2O$ (2.6–9.5; average 6.64%) immediately rule out an origin from chert which has higher silica and lower alumina and alkalis. Most quartzites would also include samples with higher silica than 81% but metamorphosed arkose or acid igneous rock could equally well fit the above ranges.

Because of the predominance of SiO_2, and the constant sum effect of chemical analyses reported in percentages, it is inevitable that SiO_2 variations strongly negatively influence all other major element variations. In order to obviate this negative correlation, the major elements are considered in terms of Niggli numbers (Niggli, 1954). In these, the sum of the molecular proportions of Al_2O_3, CaO, $2Fe_2O_3 + FeO + MnO + MgO$, and $K_2O + Na_2O$, when recalculated to 100 gives the percentages of *al, c, fm,* and *alk,* all in molecular proportions, with *si* and *ti* being the molecular proportions of SiO_2 and TiO_2 reduced to the same basis as the first elements; k = mol. prop. K_2O/mol. prop. $(K_2O + Na_2O)$ and *mg* is the mol. prop. MgO/mol. prop. $(2Fe_2O_3 + FeO + MnO + MgO)$.

To distinguish between quartzofeldspathic sedimentary and igneous rocks, two chemical approaches are likely to be most profitable: (1) to establish trends of chemical variation which are characteristically different for sedimentary and igneous suites, one being controlled by sedimentary processes, the other by igneous fractionation; (2) to identify distinctively different element concentration ranges for the two suites, either graphically or by a discriminant function. Both of these approaches have to be applied in a highly selective manner because most of the chemical variation in quartzofeldspathic rocks is very similar whatever the genesis and consists largely of variations resulting from changes in quartz and feldspar. Moreover, both igneous and sedimentary rocks have a wide range in composition. This account does not discuss the many chemical variations which are common to ortho- and para-quartzofeldspathic rocks.

Igneous and sedimentary trends of variation. Although numerous studies of igneous fractionation have emphasized the importance of Mg/Fe change, all variations that rely on *mg* fractionation are based on ferromagnesian minerals which are only minor constituents of sandstones, granites, or rhyolites. Accordingly variations based on felsic minerals will be examined first as these are potentially useful and less subject to the analytical errors inherent in determining minor and trace constituents. Of particular value in distinguishing sedimentary and igneous trends of variation is a plot of Niggli *al–alk* against *c* (fig. 2).

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TABLE I: CHEMICAL ANALYSES OF DELANEY DOME FORMATION

Sp.No.	15	37	38	39	40	41	42	43	44	45	46	47	49	50	85
SiO_2	76.92	74.34	70.82	73.00	73.84	70.78	73.45	75.64	75.49	75.42	76.15	73.50	73.45	71.44	70.87
TiO_2	0.25	0.21	1.02	0.32	0.33	0.33	0.30	0.21	0.19	0.21	0.22	0.30	0.21	0.84	0.05
Al_2O_3	9.74	12.01	13.22	11.76	12.34	13.48	13.48	10.47	10.92	11.44	11.65	12.98	12.11	12.15	11.76
Fe_2O_3	2.05	1.40	2.18	2.04	1.98	2.36	2.16	1.88	2.08	2.14	1.85	2.10	1.54	2.56	1.96
FeO	1.02	1.28	1.52	1.30	1.49	1.83	1.54	0.72	0.73	0.59	0.40	2.39	1.23	2.19	2.95
MnO	0.05	0.04	0.05	0.06	0.04	0.06	0.06	0.04	0.02	0.04	0.05	0.05	0.04	0.06	0.08
MgO	0.91	0.50	2.08	0.77	0.42	0.34	0.60	0.20	0.22	0.24	0.10	1.72	0.79	1.53	2.72
CaO	1.64	0.38	1.91	1.44	0.95	1.92	1.01	0.18	0.37	0.70	0.53	1.56	0.26	1.49	2.14
Na_2O	3.21	2.23	2.18	4.06	3.64	3.99	2.51	2.55	2.12	2.72	2.43	2.29	1.76	5.52	3.78
K_2O	1.81	6.52	2.82	2.80	4.40	3.03	4.40	5.43	6.60	6.00	6.83	2.85	7.30	0.51	1.73
P_2O_5	0.04	0.03	0.08	0.09	0.07	0.06	0.06	0.03	0.03	0.03	0.02	0.05	0.06	0.19	0.06
H_2O+	0.78	0.25	1.82	1.59	0.66	0.82	1.30	0.85	0.06	0.11	0.00	1.71	0.72	0.50	1.20
CO_2	0.02	0.10	0.09	0.10	0.00	0.06	0.00	0.20	0.13	0.20	0.33	0.21	0.00	0.00	0.14
Total	98.44	100.27	99.05	99.33	100.16	99.05	100.87	98.73	98.96	99.84	100.57	101.71	99.47	98.98	99.89
Ba ppm	1015	1281	406	839	667	884	1017	696	739	637	675	727	1247	261	971
Ce	46	38	58	56	56	74	72	47	60	75	62	80	49	65	75
Co	3	2	0	6	4	7	9	3	4	4	1	5	2	10	14
Cr	138	82	107	14	15	10	10	39	30	16	14	62	38	40	119
Cu	20	0	0	0	0	0	0	0	0	0	7	6	0	0	20
Ga	10	17	21	18	12	14	11	14	16	15	14	16	12	20	16
La	15	10	29	18	17	25	23	10	23	33	25	39	16	29	37
Nb	18	18	20	16	14	15	14	17	19	18	16	17	12	16	15
Ni	0	0	1	0	0	0	0	0	0	0	0	0	0	5	15
Pb	11	32	31	20	34	23	31	16	47	20	43	18	11	12	8
Rb	31	145	124	118	68	106	154	101	137	114	160	115	88	8	35
Sr	89	167	205	147	135	337	84	260	294	306	58	176	306	370	141
Th	13	12	17	11	12	14	13	17	12	14	16	14	14	6	13
Y	31	12	41	23	31	21	27	25	30	33	33	40	24	44	42
Zn	70	36	29	41	38	38	35	49	40	28	37	50	32	53	105
Zr	377	240	315	227	307	359	334	275	278	300	270	322	181	348	314

Niggli Values

	15	37	38	39	40	41	42	43	44	45	46	47	49	50	85
al	37.00	42.45	39.43	38.58	40.43	40.50	43.95	42.22	41.25	41.07	42.85	39.23	41.63	34.98	31.42
fm	24.18	17.21	30.42	29.98	18.69	19.44	21.07	15.84	16.05	14.99	11.71	31.50	19.63	29.49	36.36
c	11.33	2.44	10.36	8.59	5.66	10.49	5.99	1.32	2.54	3.54	3.54	8.57	1.63	7.80	10.43
alk	27.50	37.91	19.80	31.85	35.22	29.57	28.99	40.62	40.16	39.37	41.90	20.71	37.12	27.73	21.69
si	495.70	446.10	358.40	406.30	410.50	360.83	406.37	517.57	483.87	459.37	457.27	376.88	428.44	348.96	322.31
k	0.27	0.66	0.46	0.31	0.44	0.33	0.54	0.58	0.67	0.59	0.65	0.45	0.73	0.06	0.23
ti	1.21	0.95	3.88	1.34	1.38	1.27	1.26	1.08	0.92	0.96	1.03	1.16	0.92	3.09	1.71
mg	0.36	0.26	0.52	0.30	0.19	0.13	0.23	0.13	0.13	0.15	0.08	0.42	0.35	0.38	0.51
w	0.64	0.50	0.56	0.59	0.54	0.54	0.56	0.70	0.72	0.77	0.81	0.44	0.53	0.51	0.37

Sp.No.	102	133	134	135	136	137	138	139	140	141	143	144	145	146	147
SiO_2	76.62	73.97	74.87	74.34	75.38	77.30	71.43	74.43	74.04	73.66	75.41	73.53	79.66	71.40	75.54
TiO_2	0.27	0.27	0.48	0.28	0.23	0.17	0.40	0.24	0.38	0.21	0.25	0.24	0.24	0.48	0.23
Al_2O_3	11.52	12.60	10.88	12.53	10.34	10.12	12.00	11.57	12.09	11.92	11.48	11.83	9.74	12.81	11.65
Fe_2O_3	0.26	2.21	2.05	2.45	1.79	2.01	2.06	0.49	1.87	1.37	2.04	1.87	1.42	2.34	2.12
FeO	3.06	1.25	2.49	0.79	1.53	0.94	2.57	1.26	2.63	1.63	1.11	1.32	0.50	2.05	0.84
MnO	0.04	0.03	0.05	0.06	0.05	0.05	0.05	0.03	0.04	0.04	0.04	0.05	0.03	0.06	0.04
MgO	0.59	1.29	1.33	0.58	0.65	0.46	2.39	0.27	0.93	0.55	0.55	0.69	0.23	1.22	0.66
CaO	1.62	1.10	0.66	2.34	0.59	0.30	0.93	0.41	0.86	0.55	0.16	0.34	0.29	2.61	0.45
Na_2O	5.01	2.85	5.61	3.68	4.94	2.12	1.83	3.34	3.43	4.34	3.10	1.86	1.71	2.08	2.98
K_2O	0.50	2.53	0.34	1.68	3.61	5.29	4.75	4.87	2.37	3.19	3.66	6.75	6.16	2.95	4.60
P_2O_5	0.04	0.05	0.09	0.07	0.03	0.02	0.07	0.04	0.08	0.03	0.04	0.04	0.04	0.10	0.03
H_2O+	0.53	1.56	0.97	1.18	0.85	0.62	1.64	0.60	1.20	0.77	0.77	1.28	0.34	1.82	0.53
CO_2	0.07	0.19	0.07	0.05	0.06	0.13	0.09	0.21	0.18	0.15	0.24	0.13	0.19	0.17	0.14
Total	100.13	99.90	99.89	100.01	100.05	99.53	100.21	99.14	98.72	98.41	98.87	99.93	100.55	100.09	99.81
Ba ppm	187	1022	83	730	1072	1133	772	727	643	919	711	674	1781	986	720
Ce	63	64	73	56	41	45	77	40	59	50	60	43	40	67	46
Co	3	5	5	2	3	1	7	2	2	1	2	2	0	4	1
Cr	36	57	34	63	54	83	12	134	9	15	21	21	62	154	0
Cu	0	4	2	12	4	0	6	8	8	0	3	5	7	2	0
Ga	14	17	18	15	16	14	15	16	15	16	16	16	11	16	14
La	23	35	34	31	22	23	32	15	30	19	32	26	17	35	23
Nb	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ni	-	1	1	0	0	0	6	0	2	0	0	0	1	7	2
Pb	9	21	10	22	25	30	26	25	17	19	14	24	17	25	22
Rb	8	99	10	26	99	100	103	81	81	59	106	126	105	135	83
Sr	142	157	90	186	124	71	113	67	109	95	71	38	62	184	76
Th	14	14	4	18	1	13	12	14	11	14	16	14	13	11	14
Y	46	33	76	27	35	23	18	28	28	32	35	29	29	29	43
Zn	30	51	59	36	43	43	52	35	32	41	38	92	22	55	30
Zr	332	261	527	208	280	194	229	257	211	259	221	240	256	250	263

Niggli Values

	102	133	134	135	136	137	138	139	140	141	143	144	145	146	147
al	39.16	42.16	34.88	41.25	34.99	40.57	35.12	41.41	42.32	41.15	43.48	41.05	42.62	38.64	41.73
fm	20.96	26.29	30.50	18.82	20.65	20.30	36.07	17.39	23.48	18.83	21.10	20.84	13.58	27.09	19.94
c	10.01	6.69	3.85	14.01	3.63	2.19	4.95	2.67	5.47	3.45	1.10	2.14	2.31	14.31	2.93
alk	29.86	24.85	30.77	25.92	40.73	36.94	23.86	38.53	28.73	36.57	34.32	35.97	41.49	19.95	35.39
si	411.99	419.99	407.29	415.30	432.88	525.86	354.77	452.02	439.71	431.50	484.62	432.91	591.48	365.44	459.12
k	0.06	0.37	0.04	0.23	0.32	0.62	0.63	0.49	0.31	0.33	0.44	0.70	0.70	0.48	0.50
ti	1.17	1.15	1.96	1.09	1.99	0.87	1.49	1.10	1.70	0.93	1.21	1.06	1.34	1.85	1.05
mg	0.24	0.42	0.35	0.26	0.27	0.23	0.49	0.14	0.35	0.26	0.25	0.29	0.19	0.34	0.30
w	0.07	0.61	0.43	0.74	0.51	0.66	0.42	0.57	0.14	0.43	0.62	0.56	0.72	0.51	0.69

Table I (cont.)

Sp.No.	163	164	165	166	167	168	169	170	4492	4493	4494	4495	4496	4497	4498
SiO_2	75.32	73.45	76.17	71.24	68.98	73.28	70.28	75.96	65.26	70.94	76.24	75.06	74.05	71.38	71.31
TiO_2	0.33	0.24	0.54	0.57	0.62	0.31	0.60	0.30	0.85	0.28	0.31	0.37	0.39	0.34	0.68
Al_2O_3	11.91	11.59	11.32	12.60	13.15	12.78	12.69	12.46	14.08	11.64	11.41	11.73	12.11	12.21	11.26
Fe_2O_3	1.90	1.87	1.61	2.16	3.13	2.38	3.01	1.97	2.74	0.00	1.67	1.59	1.80	2.24	2.19
FeO	1.31	1.60	2.40	2.79	2.44	0.93	2.18	1.30	3.45	6.29	1.23	0.72	1.85	1.61	2.77
MnO	0.04	0.04	0.05	0.05	0.06	0.04	0.05	0.05	0.07	0.04	0.03	0.04	0.04	0.07	0.07
MgO	1.10	0.88	0.88	1.38	1.95	0.78	1.34	0.91	1.76	0.82	0.72	0.13	0.91	1.16	1.29
CaO	0.98	0.23	1.32	3.16	2.89	1.56	3.54	1.03	2.68	2.75	0.95	0.42	1.23	2.25	1.51
Na_2O	3.47	1.59	2.90	2.95	2.91	2.91	2.66	3.63	4.55	2.78	4.50	1.79	4.96	2.84	3.72
K_2O	1.84	6.92	1.83	1.93	1.88	3.22	1.49	1.76	1.86	2.04	2.07	7.69	0.67	3.08	2.87
P_2O_5	0.07	0.04	0.10	0.11	0.10	0.08	0.12	0.07	0.19	0.07	0.08	0.04	0.09	0.06	0.13
H_2O+	1.74	1.26	1.98	2.26	2.64	2.32	1.47	1.81	0.97	1.44	1.19	0.04	0.52	1.77	1.77
CO_2	0.16	0.00	0.15	0.13	0.21	0.51	0.00	0.00	0.21	0.09	0.07	0.05	0.11	0.10	0.02
Total	100.17	99.17	101.25	101.32	100.96	100.82	99.43	101.25	98.67	99.18	100.47	99.67	99.73	99.11	99.59
Ba ppm	461	681	616	458	568	937	395	401	534	748	626	1257	144	1088	114
Ce	41	54	44	62	43	52	54	54	66	40	57	52	51	65	30
Co	2	4	5	8	12	1	12	4	10	3	0	3	5	8	11
Cr	15	45	29	31	36	18	206	0	25	34	4	62	121	10	43
Cu	0	5	4	11	9	3	5	1	10	0	3	17	23	5	22
Ga	16	16	13	16	19	14	18	16	17	16	15	14	11	17	18
La	20	23	17	29	14	21	23	23	29	14	30	24	53	29	20
Nb	-	-	-	-	-	-	-	-	-	-	-	14	13	16	14
Ni	0	1	5	10	17	0	14	0	8	2	0	2	4	0	2
Pb	21	20	20	22	23	32	18	20	20	27	26	25	23	18	16
Rb	69	126	54	91	131	115	84	73	46	96	60	148	21	97	63
Sr	174	44	138	190	213	165	265	119	156	205	97	50	77	195	77
Th	11	12	7	12	11	12	12	15	11	12	13	12	11	10	15
Y	23	25	16	26	20	20	23	26	42	19	27	24	31	48	26
Zn	38	43	49	49	65	44	57	39	147	37	31	32	33	48	59
Zr	268	265	215	231	254	217	240	203	361	210	213	153	271	300	252
Niggli Values															
al	41.85	39.97	40.20	35.51	34.96	42.11	35.81	43.16	34.10	33.82	40.06	43.22	39.76	37.70	33.89
fm	24.83	23.74	27.30	28.73	32.94	20.86	29.14	23.07	31.11	31.96	20.01	12.46	23.72	24.94	30.07
c	6.26	1.44	8.52	16.19	13.97	9.34	18.16	6.49	11.80	14.53	6.06	2.81	7.34	12.63	8.26
alk	27.06	34.86	23.98	19.57	18.14	27.69	16.90	27.28	23.00	19.70	33.86	41.51	29.17	24.72	27.77
si	449.08	432.13	458.99	340.70	311.15	409.67	336.48	446.43	268.14	349.70	454.24	469.23	412.56	373.99	364.22
k	0.26	0.74	0.29	0.30	0.30	0.41	0.27	0.24	0.21	0.33	0.23	0.74	0.08	0.42	0.34
ti	1.48	1.06	2.45	2.05	2.10	1.30	2.16	1.33	2.63	1.04	1.39	1.74	1.63	1.34	2.61
mg	0.39	0.32	0.29	0.34	0.40	0.31	0.33	0.35	0.35	0.19	0.32	0.10	0.32	0.36	0.33
w	0.57	0.51	0.38	0.41	0.54	0.70	0.55	0.58	0.42	0.00	0.55	0.67	0.47	0.56	0.42

Sp.No.	4499	4500	4501	4502	4503	4504	4505	4506	4507	4508	4509	4510	4511	4512	Average
SiO_2	73.82	74.28	72.85	71.63	65.35	69.39	67.95	71.12	70.05	70.99	73.89	78.50	78.33	77.69	73.64
TiO_2	0.36	0.24	0.35	0.39	0.71	0.62	0.61	0.55	0.59	0.56	0.22	0.18	0.23	0.28	0.37
Al_2O_3	12.15	11.75	11.77	13.12	14.17	13.12	13.90	12.57	12.66	12.48	12.21	10.77	10.62	11.04	12.01
Fe_2O_3	1.93	2.03	1.92	1.99	2.47	2.31	2.41	2.09	2.73	2.25	2.32	2.00	2.28	1.57	2.02
FeO	2.37	1.20	1.96	2.26	3.57	3.02	3.43	2.75	2.27	2.65	1.03	0.69	0.70	1.25	1.68
MnO	0.05	0.04	0.04	0.05	0.05	0.06	0.06	0.06	0.06	0.05	0.05	0.03	0.03	0.05	0.05
MgO	1.07	0.79	1.09	1.43	2.69	1.35	1.93	1.87	1.44	1.03	0.71	0.18	0.14	0.36	0.91
CaO	0.59	0.08	0.18	0.53	3.55	1.06	1.32	1.29	3.19	1.33	1.60	0.38	0.23	1.06	1.28
Na_2O	5.60	2.63	3.12	4.17	3.44	3.75	4.65	3.72	1.78	3.29	1.25	3.06	3.84	3.55	3.19
K_2O	1.13	5.31	5.22	4.16	1.63	3.21	1.48	2.12	2.48	3.78	4.84	4.32	3.07	2.55	3.45
P_2O_5	0.05	0.05	0.05	0.05	0.13	0.11	0.12	0.11	0.11	0.11	0.04	0.03	0.05	0.04	0.07
H_2O+	1.47	1.54	1.61	1.42	2.34	2.02	2.25	1.20	2.20	1.01	1.10	0.00	0.11	0.38	1.11
CO_2	0.05	0.40	0.85	0.14	0.07	0.09	0.03	0.05	0.08	0.07	0.80	0.14	0.07	0.03	0.13
Total	100.64	100.34	101.01	101.43	100.17	100.11	100.14	99.50	99.64	99.60	100.06	100.28	99.70	99.80	99.91
Ba ppm	202	696	576	628	619	688	327	710	631	898	596	1088	612	568	717
Ce	54	55	64	50	70	60	75	48	99	61	70	40	58	46	56
Co	3	2	8	7	10	12	15	11	13	11	9	4	4	6	5
Cr	10	5	8	9	61	36	38	68	34	36	13	39	9	35	46
Cu	17	19	8	7	16	8	50	12	64	14	7	10	17	11	8
Ga	16	16	13	20	18	16	16	15	10	20	18	10	9	12	15
La	38	23	26	15	36	38	47	30	34	28	36	19	29	26	26
Nb	14	13	15	20	14	13	11	13	57	57	14	9	9	15	18
Ni	0	0	0	0	11	8	10	10	9	10	0	1	0	1	3
Pb	9	43	17	17	32	22	19	41	25	24	23	22	12	22	22
Rb	29	115	71	75	80	85	44	58	137	99	149	83	57	58	89
Sr	72	43	47	91	311	92	110	138	908	123	101	83	51	124	151
Th	14	13	13	15	14	12	9	10	15	14	14	11	7	13	12
Y	64	27	54	58	31	25	28	26	26	23	36	22	37	33	31
Zn	61	94	53	56	69	58	64	58	194	56	59	36	38	35	49
Zr	462	236	371	450	284	284	310	259	79	73	0	150	244	252	260
Niggli Values															
al	37.74	41.58	38.13	37.69	32.90	37.13	36.22	36.30	36.78	37.10	42.64	42.81	41.84	42.05	39.33
fm	26.51	22.27	25.88	26.90	34.88	30.13	33.42	32.63	30.06	27.46	21.72	15.85	17.18	17.86	23.67
c	3.33	0.51	1.06	2.77	14.99	6.25	6.77	16.85	7.19	10.16	2.75	2.72	7.34	7.67	7.67
alk	32.42	35.64	34.93	32.64	17.24	27.29	24.11	24.30	16.81	28.25	25.48	38.59	38.26	32.75	29.37
si	389.10	445.96	400.44	349.15	257.45	333.17	300.44	348.48	345.31	358.07	437.86	529.43	523.67	502.07	408.10
k	0.12	0.57	0.52	0.40	0.24	0.36	0.17	0.27	0.48	0.43	0.72	0.48	0.32		0.42
ti	1.43	1.08	1.45	1.43	2.10	2.24	2.03	2.03	2.19	2.12	0.98	0.91	1.16	1.12	1.53
mg	0.32	0.32	0.35	0.39	0.45	0.32	0.38	0.42	0.35	0.28	0.29	0.11	0.10	0.19	0.32
w	0.42	0.60	0.47	0.44	0.38	0.41	0.39	0.41	0.52	0.43	0.67	0.72	0.75	0.53	0.52
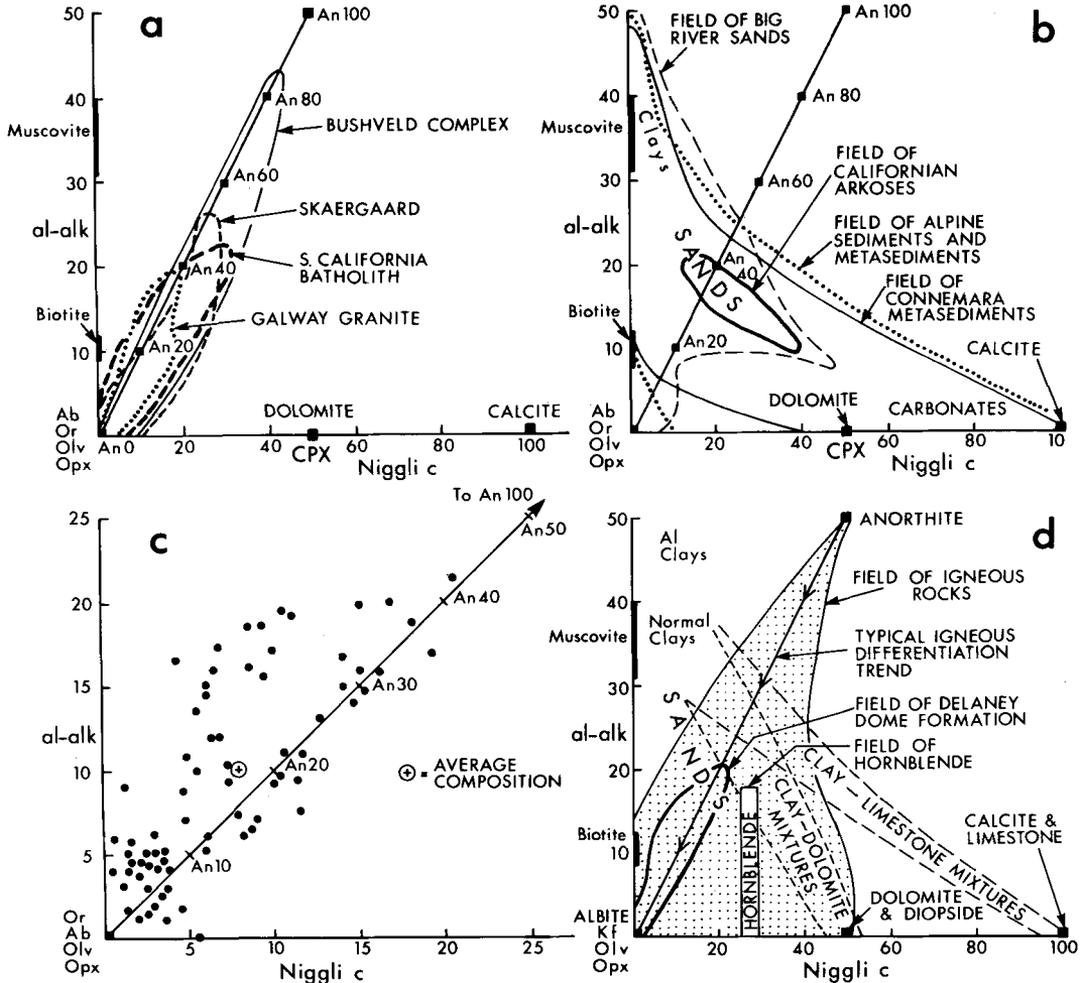
FIG. 2. Niggli *al–alk* against *c* plots. (*a*) Igneous rocks. Fields of four igneous suites outlined; also the feldspar variation line An$_{0-100}$ in which K feldspar and albite, An$_0$, plot at zero. (*b*) Sediments. Fields of variation of four typical sedimentary suites (see text) are shown and also the positions of important sedimentary rock types and the feldspar line. (*c*) Delaney Dome Formation, showing variation close to the feldspar line. (*d*) Igneous and sedimentary fields. Arrows on the feldspar line show the direction of normal igneous fractionation. Stippled area is the field of igneous rocks (which extends to negative *al-alk* values) excluding carbonatites. Mixtures of various common sediments indicated and the Delaney Dome Formation (from *c*).

On this plot albite (An$_0$), K feldspar, olivine, and orthopyroxene all plot at the origin while anorthite An$_{100}$ plots at *al-alk* 50, *c*.50. Consequently a line joining An$_0$ to An$_{100}$ shows the total variation produced by varying compositions and modal proportions of K feldspar and plagioclase, two of the major felsic minerals. Consequently, it is predictable that most igneous differentiation series will cluster around and roughly parallel the feldspar line and this is well shown by four representative

igneous suites, the Bushveld Complex (from ultra-basic to granitic), Skaergaard (gabbro to grano-phyre), the South California batholith (gabbro to granite), and the Galway Granites (granodiorite to alkali granite). Details of these plots and of other igneous series are given in Leake (1969). Of the major igneous minerals, only Ca clinopyroxene (augite, etc.) plots significantly away from the general feldspar line; biotite and hornblende are only slightly off the main trend. Changes in the

proportions of quartz have no influence on this plot. As nearly all differentiating igneous series increase in K feldspar, quartz, and albitic plagioclase with decline of anorthitic plagioclase, typical igneous variation is well represented by the plagioclase line with variation towards the origin as shown in fig. 2. This figure also depicts the field of igneous rocks (excluding carbonatites) as defined by the positions of the principal igneous minerals, olivine, pyroxenes, feldspars, hornblende, and biotite.

On this plot sedimentary variations have quite different trends to those of igneous rocks. Clays, being rich in *al-alk* and generally poor in Ca, plot on one side of the igneous field and trend while dolomites and limestones plot on the other side. Typical quartz arenites, arkoses, and greywackes, being dominated by quartz and feldspar, overlap the centre of the igneous field. But mixtures of (1) clays or shales with quartz arenites, arkoses, or greywackes, (2) clays or shales with dolomites or limestones, or (3) quartz arenites with dolomites or limestones, all characteristically give trends nearly at right angles to the igneous trend as shown by 4 representative sedimentary series; about 250 alpine sediments and metasediments compiled by Niggli (references in Leake, 1969), over 250 Connemara metasediments (Leake *et al.*, 1975; Senior and Leake, 1978; Leake, 1980), 26 Californian arkoses (Van de Kamp *et al.*, 1976), and 43 representative sand analyses from the world's largest rivers, kindly provided by P. E. Potter. Thus sedimentary variation is essentially from high *al-alk* with low *c* towards lower *al-alk* and increasing *c* for the three major sedimentary suites of shales, siliciclastic sandstones, and carbonates.

The Delaney Dome Formation clearly shows a distinct igneous trend consistent only with an igneous origin (fig. 2c).

Although emphasis has been placed on circumventing the influence of silica changes on other elements, silica variation can in itself be useful, as major variation in silica occurs in most sedimentary and igneous rocks. Plots which involve silica or Niggli *si* against *ratios* of other oxides or molecular amounts, or plots against trace elements, have potential in the present problem. Thus *si* against *mg* plots give a strong negative correlation because silica generally increases in igneous differentiation as Mg/Fe falls, this being well recognized in numerous igneous suites. In sedimentary rocks a wide scatter of *si* and *mg* values occurs giving a pattern quite unlike that characteristic of igneous suites. In particular very high *si* values occur in siliciclastic sandstone and arkoses, frequently exceeding 500 or 1000 and reaching up to

values in excess of 10 000. Coupled with high values is a wide scatter. Fig. 3 displays these points (note two scale changes on the *si* axis). It should be noted that of the 43 analyses of big river sands available, only 13 have *si* < 500, whereas only 8 of the Delaney Dome analyses have *si* > 500 and none exceed 700. In igneous suites the range of *si* and *mg* is relatively limited, whereas sediments show a wide scatter, as there is no necessary correlation between Mg/Fe (which is largely controlled by the clay minerals, detrital Fe oxides and ferromagnesian minerals) and *si*, which is largely in quartz and feldspars. Only sedimentary suites involving dolomite show consistent negative correlations of *si* and *mg*, and necessarily, because dolomite is silica-free, such suites either have much lower values of *si* than the present rocks or higher Ca and Mg, or both characteristics.

The Delaney Dome rocks clearly match best to the igneous trend of increasing *si* with fall of *mg* and also display similar amounts of scatter to that shown by typical igneous suites of which the S. California batholith is quite representative (fig. 3). Low levels of MgO, as in the present rocks, must undoubtedly contribute to the scatter in any plot relying on *mg*, especially when MgO is determined by XRF analysis.

From the *al-alk* against *c* diagram it can be deduced that with igneous differentiation *al-alk* declines and therefore there should be a positive correlation between *mg* and *al-alk*, a plot which (as with the *si* vs. *mg* plot) combines a feature based largely on the mafic minerals with one based largely on the salic minerals. Fig. 3 shows that the present samples exhibit an overall positive correlation of *mg* and *al-alk* which is only consistent with igneous fractionation; sedimentary rocks either show no correlation or tend to have a negative correlation as instanced by the Connemara metasediments and Californian arkoses.

The scatter in fig. 3 emphasizes the need to study a considerable number of samples; a small number could give a misleading impression. Particularly important in all studies of variation trends is the need to collect samples covering as full a *range* of variation as possible; merely collecting typical 'average' samples could result in clusters of points on the geochemical plots in which variation trends are not apparent. Arithmetic averages might be closely similar for igneous and sedimentary suites. Thus in sampling for geochemical work of this kind unusual samples need to be included as well as typical ones. Because Niggli *al-alk*, *c*, and *mg* are all independent of the amount of SiO_2 in the analysis, varying proportions of quartz have little influence on the trends and thus quartz arenites, which can contain over 90% SiO_2, have one major
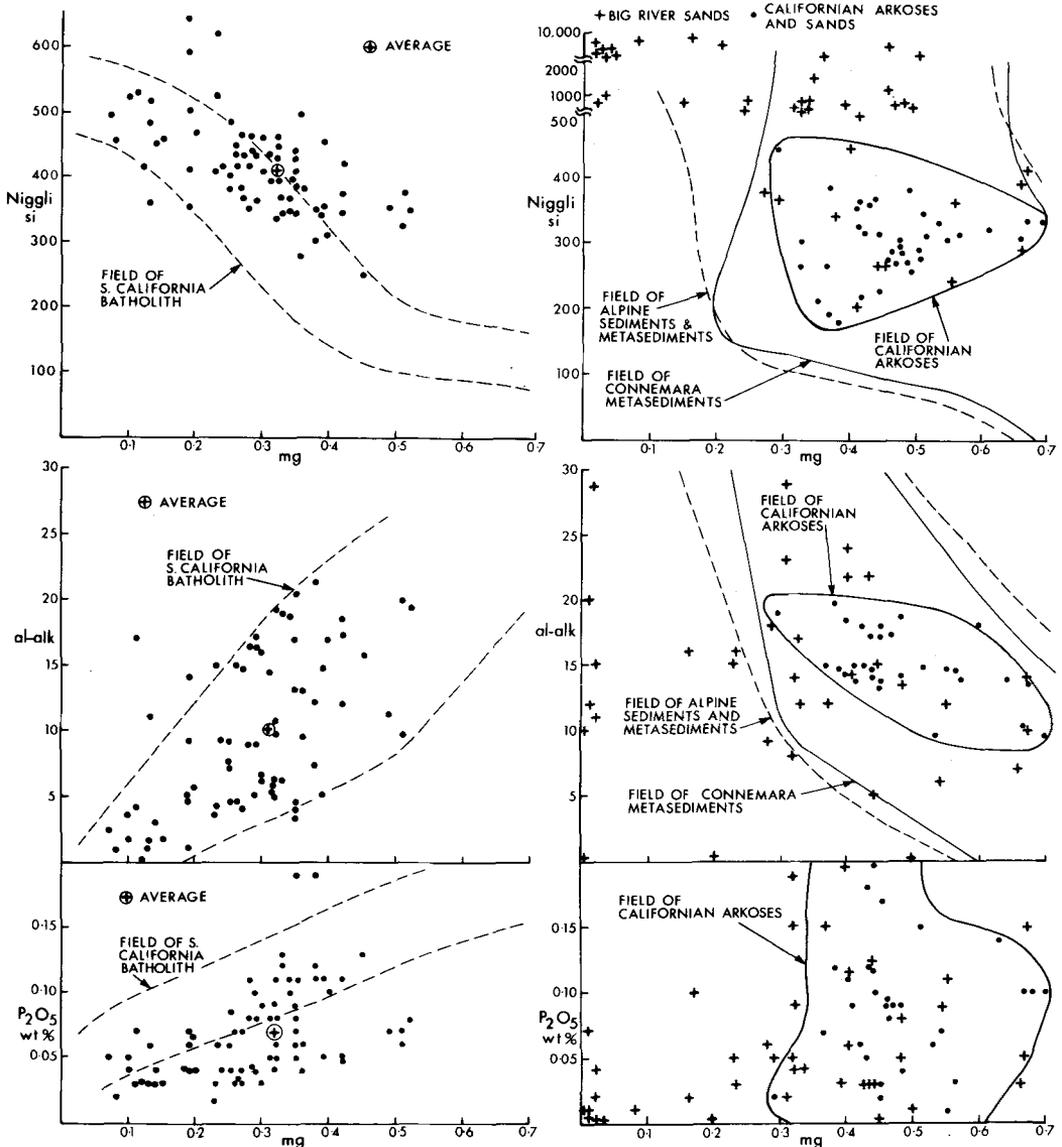
FIG. 3. Plots of Niggli *mg* against *si*, *al–alk*, and P_2O_5 wt. % for the Delaney Dome Formation and the S. California batholith (left hand side) and typical sedimentary series (right hand side). The big river sands are shown by crosses and because of the wide scatter, which also extends outside the range of the plot, no field is defined for these analyses. The solid spots are Californian arkoses representative of variation in arkoses; the Alpine and Connemara fields cover a wide range of sediments and sedimentary rocks (references in text).

variable removed. Plots of Al_2O_3 wt. % minus $Na_2O + K_2O$ wt. % and of CaO wt. %, or even of the molecular proportions of these values, diminish as SiO_2 wt. % increases.

Other plots that are useful in the solution of this problem include *mg* against P_2O_5 (fig. 3) and Zr in

which acid igneous rocks show fall in *mg* with fall in P_2O_5 and Zr as apatite and zircon crystallization depletes the magma of P and Zr. In contrast, neither of these elements vary systematically with *mg* in metasediments, as neither apatite nor zircon are related to the Fe- and Mg-bearing minerals in

sediments, being determined neither by the salic nor femic minerals.

Although Cr and Ni variation with mg is well established as a reliable indicator of igneous fractionation in basic magmas, these elements are much less useful in acid igneous rocks because Cr and Ni have very low abundances in such rocks and mg has considerable experimental scatter. Typically Cr and Ni values in sediments are higher than in granites and rhyolites. Thus typical quartz arenites and arkoses have Ni 20–40 ppm (Wedepohl, 1969; Van de Kamp et al., 1976) whereas rhyolites average less than 10 ppm and granites 7–15 ppm (Wedepohl, 1969). The present samples average only 3 ppm Ni and although possessing higher Cr values (av. 46 ppm) are still low for a sediment. Ni–mg and Cr–mg plots (not reproduced) do not conflict with an igneous origin.

Although plots which involve al–alk are subject to the criticism that alkalis are among the most mobile of the common elements in rocks, plots which involve mg, si, Zr, and P are all independent of alkali variation. Accordingly if such plots give an ortho or para indication consistent with that given by al–alk plots, as in the present instance, then there seems no reason to regard the al–alk parameter as unreliable. If the al–alk derived deductions conflict with those derived from other evidence then a close examination of the nature of the al–alk variation is called for. The commonest form of alkali metasomatism in metamorphic rocks involves feldspathization and such metasomatism should not be difficult to detect because the ratios Na/Ca, Na/K, or K/Ca should progressively change with feldspathization towards those ratios found in the stable feldspar (i.e. the porphyroblasts) because the control on chemical composition with respect to the mobile elements is the composition of the stable porphyroblastic feldspar. If no change in rock composition occurs with respect to Na/Ca, Na/K, or K/Ca, depending whether the feldspar is K feldspar or plagioclase, then the feldspathization is probably isochemical recrystallization. Because each feldspar composition, whether plagioclase or K feldspar, has a characteristic al–alk value, the al–alk values of feldspathized alkali metasomatized rocks should cluster around this characteristic value rather than be scattered along an igneous or sedimentary trend thus enabling the recognition of alkali movement connected with feldspathization. Other types of alkali movement may be more difficult to detect but can be suspected if al–alk plots consistently deviate from the trend expected using the evidence of other elements or ratios. Indeed an alkali metasomatized rock can be expected to display neither a sedimentary nor an igneous al–alk trend but a metasomatic trend of variation of al–alk

with little change in c (unless Ca has also moved). Such a vertical variation on the al–alk against c plot has been found in alkali-metasomatized material (Leake, 1970).

Average composition. Table II shows that the average composition of the Delaney Dome Formation major oxides matches fairly closely that of typical rhyolite or calc alkali rhyolite, the main differences being the rather higher Fe, Mg, and Ca and lower Al and K of the Delaney Dome rocks. This is consistent with a slightly less differentiated magma than those which form the basis of the averages cited. The Delaney Dome rocks equally well match with typical granites, being again rather richer in Fe and Mg and lower in Al and K than the average granites listed. There is also, however, rather more Si and less P in the Delaney Dome Formation. Little more can be deduced by comparing averages which encompass considerable variations in the rocks averaged but it is notable that most analyses of rhyolites consulted show distinctly lower P than granites of otherwise similar major element chemistry (see fig. 3). This may result from intratelluric crystallization of apatite within plutons in which F, Cl, and OH are available to crystallize apatite [the higher H_2O of the rhyolites compared with the granite in Table II is almost certainly a function of post-magmatic addition of water to the rhyolites].

Although individual siliciclastic sandstone or arkose analyses closely similar to the average composition of the Delaney Dome rocks no doubt exist, Table II shows that, on the whole, quartz arenites and arkoses are richer in Si and Ca and poorer in Al, Na, and K (i.e. such sediments have relatively more quartz and less alkali feldspar). Nevertheless sole reliance on average compositions is unsatisfactory because both igneous and sedimentary rocks show great diversity, and trends of variation related to the formative processes are likely to be more reliable.

Conclusions and discussion

The Delaney Dome Formation is a deformed low grade metamorphosed quartzofeldspathic igneous rock, originally a rhyolite or granite. Although geochemically it has not been possible to distinguish between these two alternatives, the extremely fine grain size (< 0.1 mm), the total lack of quartz porphyroclasts and the rare euhedral orthoclase and albitic plagioclase crystals strongly suggests a sheared rhyolite or ignimbrite, perhaps originally rich in volcanic glass. The Carlsbad–albite twinning in the plagioclase suggests an igneous feldspar because metamorphic plagioclase does not normally contain Carlsbad and albite twinning. The lack of

TABLE II: AVERAGE CHEMICAL ANALYSES OF QUARTZOFELDSPATHIC ROCKS

	1	2	3	4	5	6	7	8
SiO_2	73.64	72.82	73.66	71.30	72.08	77.1	78.66	80.15
TiO_2	0.37	0.28	0.22	0.31	0.37	0.3	0.25	0.42
Al_2O_3	12.01	13.27	13.45	14.32	13.86	8.7	4.78	6.43
Fe_2O_3	2.02	1.48	1.25	1.21	0.86	1.5	1.08	1.29
FeO	1.68	1.11	0.75	1.64	1.67	0.7	0.30	1.10
MnO	0.05	0.06	0.03	0.05	0.06	0.2	0.01	0.05
MgO	0.91	0.39	0.32	0.71	0.52	0.5	0.17	0.85
CaO	1.28	1.14	1.13	1.84	1.33	2.7	5.52	3.32
Na_2O	3.19	3.55	2.99	3.68	3.08	1.5	0.45	1.19
K_2O	3.45	4.30	5.35	4.07	5.46	2.8	1.32	1.20
P_2O_5	0.07	0.07	0.07	0.12	0.18	0.1	0.08	0.06
H_2O+	1.11	1.10	0.78	0.64	0.53	0.9	1.33	0.92
CO_2	0.13	0.08		0.05		3.0	5.04	2.10

1. Average of 74 analyses of the Delaney Dome Formation.

2. Average of 670 typical rhyolites (Le Maitre, 1976).

3. Average calc alkali rhyolite (Nockolds, 1954) [of 22].

4. Average of 2485 granites (Le Maitre, 1976).

5. Average calc alkali granite (Nockolds, 1954) [of 72].

6. Average arkose (Pettijohn, 1963).

7. Average of 253 sandstones (Pettijohn, 1963).

8. Average of 43 big river sands (Potter, pers.comm.).

microcline in euhedral K feldspar crystals also suggests a non-metamorphic origin. Chemically the low P_2O_5 values agree particularly well with a rhyolite.

A number of plots have been shown to be useful in distinguishing quartzofeldspathic sediments and igneous rocks, in particular *al–alk vs. c*; *al–alk vs. mg*; and *mg vs. si*, whereas other plots such as *mg vs.* P_2O_5 and *si vs.* Zr may also be of assistance.

The Delaney Dome Formation is the foreland on to which the Dalradian rocks were thrust. The formation is likely to be fairly thick for otherwise, instead of mylonitizing the rocks under the Mannin thrust, it is likely that movement would have continued on an underlying more ductile horizon such as a shale or carbonate; there can be few less suitable rocks for a thrust zone than an unbedded acid igneous rock. Thus a substantial thickness of rhyolite is probably present which must predate 460 ± 20 Ma, the Rb–Sr age of the Mannin thrust and also the K–Ar age of lineated hornblendes in the overlying Ballyconneely amphibolite (Leake *et*

al., 1983; 1984). This, combined with the lack of pre-thrusting metamorphism of the rhyolites (assuming the igneous nature of the euhedral feldspars is correct), suggests that the volcanic rocks were not of great pre-thrust antiquity, perhaps lower to middle Ordovician, Cambrian, or late Precambrian in age. Geographically the nearest rhyolites and felsic lavas and tuffs of suitable age occur in the South Mayo trough, e.g. lower Ordovician of Tourmakeady, west of Lough Mask, although the particular rocks at Tourmakeady are associated with limestones which are unlikely to occur under the Delaney Dome. However, there are reasons for supposing that the Dalradian block of Connemara may have been strike faulted into its present position in the lower Silurian (Bluck and Leake, in prep.) and if so, the Delaney Dome Formation is unlikely to correlate directly with any rocks in the South Mayo trough.

REFERENCES

Harvey, P. K., Taylor, D. M., Hendry, R. D., and Bancroft, F. (1973) *X-Ray Spectrometry*, **2**, 33–44.

Leake, B. E. (1969) *Indian Mineral.* **10**, 89–104.

—— (1970) *J. Geophys. Res.* **75**, 349–56.

—— (1980) *Am. Mineral.* **65**, 26–36.

—— (1986) *J. Geol. Soc. London*, **143** (in press).

—— and eight others (1968) *Chem. Geol.* **5**, 7–86.

—— Tanner, P. W. G., and Senior, A. (1975) *J. Petrol.* **16**, 237–77.

—————— (1981) *The Geology of Connemara* (map). University of Glasgow.

—— —— Singh, D., and Halliday, A. (1983) *Nature*, **305**, 210–13.

—— —— Macintyre, R. M., and Elias, E. (1984) *Trans. R. Soc. Edinburgh: Earth Sci.* **75**, 165–71.

Le Maitre, R. W. (1976) *J. Petrol.* **17**, 589–637.

Niggli, P. (1954) *Rocks and mineral deposits.* Freeman, San Francisco.

Nockolds, S. R. (1954) *Bull. Geol. Soc. Am.* **65**, 1007–32.

Pettijohn, F. J. (1963) *U.S. Geol. Surv. Prof. Paper*, 440–5.

Senior, A., and Leake, B. E. (1978) *J. Petrol.* **19**, 585–625.

Van de Kamp, P. C., Leake, B. E., and Senior, A. (1976) *J. Geol.* **84**, 195–212.

Wedepohl, K. H. (1969) *Handbook of Geochemistry.* Springer-Verlag, Berlin.