Metamorphism and metasomatism of rocks of the Moine Series by a dolerite plug in Glenmore, Ardnamurchan.

(With Plate XIX.)

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Summary. A small dolerite plug in Glenmore, Ardnamurchan, has metamorphosed and partially vitrified the adjacent Moine arkoses up to a distance of 6 ft. from the contact. Chemical analyses show that the glasses produced by the metamorphism have compositions close to the ternary minimum in the system $NaAlSi_3O_8$–$KAlSi_3O_8$–SiO_2, indicating that they were formed by fractional fusion of a lowest-melting composition from the arkose. Alkali metasomatism in the metamorphosed arkoses resulted in an increase of Na_2O and a decrease of K_2O as the contact with the dolerite is approached, while an associated pelitic horizon shows an increase of K_2O content. A review of other examples of thermal metamorphism of quartzo-feldspathic rocks by basic intrusions shows that movements of alkalis are very common in this type of environment, and the possible relations of the metasomatism and the fusion are discussed.

THE partial fusion of quartzo-feldspathic and argillaceous rocks is a common feature of high-temperature thermal metamorphism such as occurs in xenoliths and at the contacts of intrusions of hot basic magma. Many examples are recorded of the partial melting of feldspathic quartzites, pelitic rocks, and acid igneous rocks, and a full bibliography of these is given in a recent paper by Wyllie (1961), while Ackermann and Walker (1960) provide another recent description of the same phenomenon. A bibliography of instances of fusion of siliceous sediments by combustion of coal is given by Venkatesh (1952), and an analogous example is the melting of calcareous sediments by combustion of hydrocarbons described by McLintock (1932). Finally, the fusion of siliceous schists and sandstones in Scottish vitrified forts (Childe and Thorneycroft, 1937), and in rocks involved in Bronze Age cremations (Davidson, 1936) may be mentioned as examples of the artificial melting of rocks, while the use of molten slags in industrial processes is too well known to require detailed reference.

In the area of Ardnamurchan to the east of the Tertiary igneous complex that forms the western end of the peninsula, there are at least fourteen plugs or dykes of basic rock that cause extensive contact alteration of the Moine Schists, into which they are intruded. They are similar to the dykes and bosses of the Moidart area referred to in the Summary of Progress of the Geological Survey for 1930 (Richey *et al.*, 1931, p. 64). Some half-dozen of the intrusions in Ardnamurchan are recorded on the Geological Survey 6-in. to the mile field sheets (the permission of the Director of the Geological Survey for the author to consult unpublished maps is gratefully acknowledged), and the remainder were discovered by the author in the course of an investigation of the Moine Schists of the Ardnamurchan area. The plugs intrude both the psammitic and the pelitic groups of the Moine Schists, and show considerable variation in outcrop from stock-like forms up to $\frac{1}{4}$ mile in diameter to dyke-like intrusions about $\frac{1}{3}$ mile in length and 20 yds. in width. The majority of the metamorphosed Moine rocks show the development of either felsitic or granophyric texture with abundant sericitic alteration (pl. XIX, fig. 1), and the igneous intrusions that caused the metamorphism are large in outcrop area and are also extensively altered. The metamorphic aureole of a dolerite plug in Glenmore, which is the subject of the present investigation, is the only example in Ardnamurchan in which glass has been found in the arkoses metamorphosed at the contact of an intrusion (pl. XIX, fig. 2). The Glenmore plug is also outstanding in being the smallest and least altered of all the intrusions that cut the Moine Schists in Ardnamurchan east of the Tertiary igneous complex.

Field description.

The Glenmore dolerite plug is intrusive into Moine arkoses $\frac{3}{4}$ mile NNE. of the road bridge over the river at Glenmore, Ardnamurchan. It forms a slight prominence on the south-west side of the ridge north-east of the track from Glenborrodale to Lochan na Carraige at a point due west of Lochan nan Caorach. The National Grid reference of the locality on the 1-in. Ordnance Survey sheet number 45 (Seventh Series) is 591638.

The plug forms an irregular hexagonal outcrop, with the south-west and north-east sides parallel with the strike of the Moine arkoses; the maximum length of the plug is 145 ft. (NW.–SE.) and the width is 85 ft. The south-western contact of the dolerite, which forms a steep crag-face overlooking the track, dips at 75° to the south-west, thus coinciding with the dip of the arkoses in the area. The contact of the dolerite and the arkose is thoroughly welded, and a thin skin of partly fused arkose adheres to the south-western side of the plug. On the south side of the plug, which is also well exposed, the contact is irregularly corrugated, suggesting that some bands of the arkose offered less resistance to emplacement of the dolerite than others. A band of pelite 4 to 6 in. thick is interbedded with the arkoses, and the dolerite forms a dyke-like apophysis of the same width extending along the plane of the pelitic band for a distance of about 1 ft. from the contact of the dolerite with the adjacent arkoses. The banding of the arkoses, and of the pelitic horizon, runs straight into the southern contact without contortion, and the dolerite appears to have made room for itself by stoping, or possibly by solution, of the arkoses from the sides of the plug, rather than by forceful intrusion. The complete absence of xenoliths of Moine rocks in the plug suggests that the dolerite was flowing over a considerable period of time, perhaps as a feeder to a lava flow, and this is confirmed by the wide aureole of thermal metamorphism surrounding the relatively small plug. There is no sign of any strongly chilled margin to the dolerite, and although the grain size is smaller in the outer 3 ft. of the plug than in the centre, the dolerite at the contact with the arkoses is still relatively coarse-grained.

Petrography.

Dolerite. Modal analyses and details of the optical properties of the principal minerals of the dolerite are given in table I.

The central part of the plug consists of olivine-dolerite with subophitic to intergranular texture in which anhedral olivine and clinopyroxene crystals up to 0·5 mm. across show a tendency to clot together in aggregates of grains. The average length of the plagioclase laths is 1·0 mm., but occasional crystals are up to 3·0 mm. long. Carbonate and a mesostasis of greenish chloritic material, which includes fine needles of pyroxene and apatite, occur interstitially to the plagioclase laths. Apart from partial serpentinisation of the olivine, the rock is very fresh.

About 3 ft. from the contact, the dolerite becomes slightly finer-grained, the average length of the plagioclase laths being 0·7 mm., with rare crystals up to 2·0 mm. long. The texture of the rock is subophitic. Olivine is absent, but may possibly be represented by patches of serpentine and carbonate. Spherical amygdales up to 2·0 mm. across are prominent in the outer part of the plug, and may be filled with carbonate or, rarely, with a zeolite mineral (not identified); carbonate is also common as grains interstitial to the plagioclase. The mesostasis consists of yellow isotropic material with pyroxene needles, and sometimes contains small isolated grains and aggregates of quartz.

At the contact with the Moine arkoses, the dolerite has much the same

TABLE I. Modal compositions (volume %) of some dolerites from the Glenmore plug, and optical properties of the principal minerals.

	1	2	3	4
Olivine ...	6·7	—	—	—
Pyroxene ...	27·3	23·0	25·0	25·4
Plagioclase ...	59·6	56·1	62·0	58·0
Iron ore ...	4·3	4·8	4·3	2·4
Carbonate ...	0·5	5·0	—	1·6
Mesostasis ...	1·6	11·1	—	12·6
Limonite ...	—	—	8·7	—
Olivine				
β ...	1·750			
2V ...	74°			
Pyroxene				
β ...	1·691	1·692	1·689	1·687
2V ...	47°	50°	49°	50°
Plagioclase				
Composition*	An_{71}	An_{72}	An_{73}	An_{71}

* Determined from the maximum extinction angle in the zone normal to (010).

1. Dolerite at the centre of the plug.
2. Dolerite 3 ft. from the contact.
3. Dolerite in contact with the fused arkose.
4. Dolerite in the apophysis along the line of the thin pelitic band.

appearance as elsewhere in the outermost 3 ft. of the plug, but contains a large proportion of limonite, possibly a weathering product of the mesostasis, which is not otherwise visible in this part of the plug. In some rocks, however, there is a patchy distribution of felsitic material, quite unlike the mesostasis of the normal types of dolerite in the plug, but very similar to the product of devitrification of the glassy part of the fused Moine arkoses, which will be described later. This felsitic material is partly interstitial and partly forms irregular rounded areas, suggesting that it may represent small fragments of arkose in various stages of assimilation into the dolerite.

In the apophysis along the line of the pelitic band, the dolerite shows a well-developed ophitic texture, due to the increased size of the pyroxene crystals, which are here up to 2·0 mm. across. The plagioclase laths are usually 0·5 mm. long, with rare crystals up to 1·5 mm. long. Spherical amygdales, usually 1·0 mm. in diameter, but sometimes as much as 7·5 mm. across, are common and are filled with carbonate. The pyroxene and plagioclase of the dolerite are both fresh, but the abundance of dark green chloritic mesostasis gives an altered appearance to the rock.

The field relations of the plug give no information regarding its age, except that it is later than the metamorphism of the Moine Schists. The freshness of the dolerite and the presence of olivine suggest that it is more likely to belong to the Tertiary igneous phase than to the Permo-Carboniferous suite of quartz-dolerite dykes and bosses.

Moine arkoses and pelite. The rocks into which the dolerite plug is intruded are thick, massive, false-bedded and pebbly, grey or white arkoses and belong to the part of the Moine Series referred to as the Glenmore Psammitic group by Richey *et al.* (1938, p. 71). The arkoses are composed of quartz, microcline, and plagioclase, variable amounts of muscovite and biotite, and accessory epidote, garnet, sphene, zircon, iron ore, apatite, and carbonate. Pelitic bands are rare in the Glenmore Psammitic group, but one is exposed *in situ* and in some large boulders about 45 ft. to the south-east of the plug; it is 4 in. thick, and is associated with micaceous and pebbly arkoses, with a subsidiary ½-in. thick seam of similar pelite on the north-east side of the main band; similar pebbly arkoses and a thin subsidiary pelite are associated with the pelitic band metamorphosed at the contact, and this almost certainly represents the identical horizon within the arkoses. A chemical analysis of the pelite is given in table IV, together with the modal composition and optical properties of the principal minerals.

Metamorphosed arkoses and pelite. Due to the thick soil and detritus cover surrounding the dolerite plug, the metamorphosed Moine arkoses are only sporadically exposed. However, a nearly complete section through the metamorphic aureole of the plug was obtained by digging a trench along the line of strike of the pelitic band on the south-east side of the plug, and specimens collected from the rock *in situ* in the trench enable the sequence of changes with progressive metamorphism to be followed in both the arkose and the pelite from about 4 ft. up to a few inches from the contact with the dolerite.

The thermally metamorphosed arkoses are grey, black, or greenish-black tough rocks with a brittle fracture and vitreous appearance in which relics of the original pebbly texture can sometimes be distinguished. The pelites are tough, splintery, grey or black rocks with pale green streaks and bands parallel to the original schistosity planes.

In the specimens farthest from the contact, the micas of both the pelite and the arkose are already thoroughly altered. The original muscovites are turbid yellow in colour, and the biotites are almost completely opaque due to the formation of iron ore, but with traces of the original brown mica still showing the pleochroism and high birefringence. A thin rim of finely crystalline potash feldspar is sometimes present as a reaction product between both types of mica and adjacent quartz grains. Garnet is still present in spongy grains, as in the original pelite, but is associated with iron ore, which appears to have separated from it. The arkose is shattered and some of the larger feldspar crystals are granulated, but there is no sign of fusion at this stage. The cross-hatched twinning of microcline is still present in the potash feldspar, which is biaxial with a high optic axial angle.

Three feet from the contact, the pelite presents much the same appearance as before, but the rims of potash feldspar between the original mica flakes and the quartz grains are more distinct (see pl. XIX, fig. 3). Basal sections of the original muscovite flakes show a hexagonally-arranged pattern of fine needles, probably of mullite (pl. XIX, fig. 4), but it was not found possible to separate the needles for precise identification on account of their very small size. In the arkose, the margins between the quartz and the feldspar grains are diffuse, and in some cases a very thin rim of glass can be distinguished. The potash feldspar is now sanidine with a small optic axial angle, and the reaction rims round the micas of the pelite can also now be identified as sanidine.

Two and a half feet from the contact with the dolerite, the potash feldspar rims (largely sericitized) round the original mica flakes of the pelite are 0·025 mm. wide, and all the relict mica has disappeared. A distinct rim of glass is always found between the quartz and the feldspar of the arkose. Relict garnet is still found in the pelite, but most of it is completely altered to iron ore and fine-grained turbid micaceous material, possibly an alteration product of cordierite.

Two feet from the contact, the reaction rims round the original micas of the pelite are up to 0·1 mm. wide and have a felsitic texture suggesting that they may represent devitrified glass from which some of the potash feldspar has crystallized as fine laths; greenish chloritic material occurs with the feldspar. The individual grains of opaque minerals derived from the biotite can now be resolved, and show the characteristic square and hexagonal cross-sections of spinel. The texture of the original schistosity of the pelite is still preserved up to this stage. In the arkose, parallel-sided channels of brownish glass are always present between the quartz and feldspar or altered mica. The feldspars have begun to recrystallize to a turbid, brownish mosaic, especially round the edges and along the cleavage cracks of the larger grains (pl. XIX, fig. 2). This resembles the initial stage of melting of albite observed experimentally by Day and Allen (1905, p. 120), a similar texture being described by

Guppy and Hawkes (1925, p. 329) as 'finger-print structure', and used by them as evidence of incipient melting of soda-orthoclase xenocrysts in a dolerite dyke in Iceland. The same texture in feldspar xenocrysts in Permian lavas in Devon was referred to as 'frit-lattice' or 'frit-channelling' by Tidmarsh (1932, p. 733), who attributed it to rapid heating and disintegration of the feldspar as a result of thermal expansion, the glass being considered to be a product of diffusion of the magma into the channels thus formed. The texture is also described by Lacroix (1893), Richarz (1924), Holmes and Harwood (1932), Davidson (1935), Knopf (1938), Larsen and Switzer (1939), Skelhorn (in discussion of Ackermann and Walker, 1960), and Wyllie (1961); the majority of these authors ascribe the texture to incipient melting of the feldspar. The small crystals of new feldspar preserve the optical orientation of the old, and, in the aureole of the Glenmore plug, as the contact with the dolerite is approached the finger-print texture spreads to cover the whole of the original detrital grain, so that eventually none of the clear feldspar remains, but the mosaic of small crystals still behaves optically as one unit. The margins of each unit frequently consist of slightly coarser crystals, suggesting that there has been some growth of new feldspar (cf. Larsen and Switzer, 1939, fig. 6, and Wyllie, 1961, p. 9).

Fifteen inches from the contact with the dolerite, the original schistosity of the pelite is locally destroyed, but trains of opaque spinel grains up to 0·03 mm. across indicate the positions of the original biotite flakes. Potash feldspar is abundant in the pelite as fine laths and skeletal crystals set in a turbid, brownish, devitrified glass, which contains rare spherical amygdales filled with carbonate, of very similar appearance to those found in the dolerite in the outermost zone of the plug.

Specimens of arkose and pelite close to the contact show the development of abundant glass, now usually turbid and brown in colour due to devitrification. In the pelite, spinel is very common in euhedral grains up to 0·1 mm. across; the smaller grains are translucent and dark brown. Thin needles of hypersthene up to 1·0 mm. long are found in both the pelite and the arkose, and feldspar occurs as lath-shaped skeletal crystals in the pelite, and as recrystallized mosaics in the arkose. Cordierite is rare, but occurs in some specimens in the characteristic rectangular and hexagonal cross-sections, often associated with recrystallized feldspar (cf. Ackermann and Walker, 1960, p. 244); the cruciform twinning of cordierite described by Wyllie (1959) in fused Torridonian arkose has not been found definitely in the aureole of the Glenmore dolerite plug.

Partly fused arkoses are found in many localities around the plug at distances up to about 6 ft. from the dolerite. They are usually black-weathering, and on fresh surfaces present a black, pitchstone-like appearance. In thin section, the glass of these buchites is almost always altered, with varying degrees of devitrification from uniformly- or patchily-brownish isotropic glass to complete recrystallization, with the occasional development of microspherulitic texture. Embayed grains and aggregates of quartz and recrystallized feldspar represent the unfused portion of the original arkose. Microlites are very common in the glass of many of the buchites; the largest are prismatic crystals of strongly pleochroic hypersthene up to 1·5 mm. long, sometimes arranged in fan-shaped sprays of curved needles. Clinopyroxene is common, in the glass of some rocks, as fringes of short prismatic crystals around residual quartz grains. In the specimens of buchite from close to the contact with the dolerite, the margins of the quartz grains against the glass are slightly blurred through the formation of lath-shaped outgrowths, which in crossed polars extinguish in the same position as the neighbouring quartz grains. These probably represent tridymite that has subsequently inverted back to quartz, and are similar to the inverted tridymite fringes described and figured by Wyllie (1961, p. 16, and pl. 2, fig. B), who gives a bibliography of other occurrences of tridymite in fused siliceous rocks. Another type of microlite forms hair-like fringes surrounding the fingerprint textured feldspars; these occur most commonly in the rocks in which the glass is partly devitrified, and in some cases it can be seen that the individual needles form prolongations from the edges of the coarser crystals at the margins of each unit of recrystallized feldspar. The remaining types of microlite are indeterminate due to their very small size; they take the form of fine opaque needles, sometimes with secondary growths resembling scopulites and margarites, and small euhedral opaque crystals, possibly of a spinel.

Veins. An interesting exposure of the contact between the dolerite and the buchite is found at the south-western corner of the plug (see fig. 1). A zone, 2 cm. wide, of white-weathering buchite occurs between the dolerite and the normal black, partly fused arkose. Contacts between this zone and the rocks on either side are sharp and thoroughly welded, but the boundary with the normal buchite has been accentuated by weathering whereas the contact with the dolerite is more difficult to see. A modal analysis of the dolerite is given in table I, which shows that it is of normal type but contains no olivine and has a large amount of limonitic alteration material. The light-weathering contact zone consists of embayed grains and aggregates of quartz and recrystallized feldspar in a felsitic groundmass that contains sporadic clinopyroxene and twinned plagioclase crystals similar to those found in the dolerite. Quartz aggregates in this zone are frequently mantled by a halo of small clinopyroxene prisms. Locally this quartzose rock-type blends into patches of more igneous appearance containing a larger proportion of pyroxene and plagioclase and a smaller amount of the fine-grained groundmass. A similar light-weathering zone of felsitic rock is found at most other exposures of the contact with the dolerite, though not usually so well displayed as here, and possibly represents a product of hybridism or contamination between the dolerite and the fused arkoses similar to that

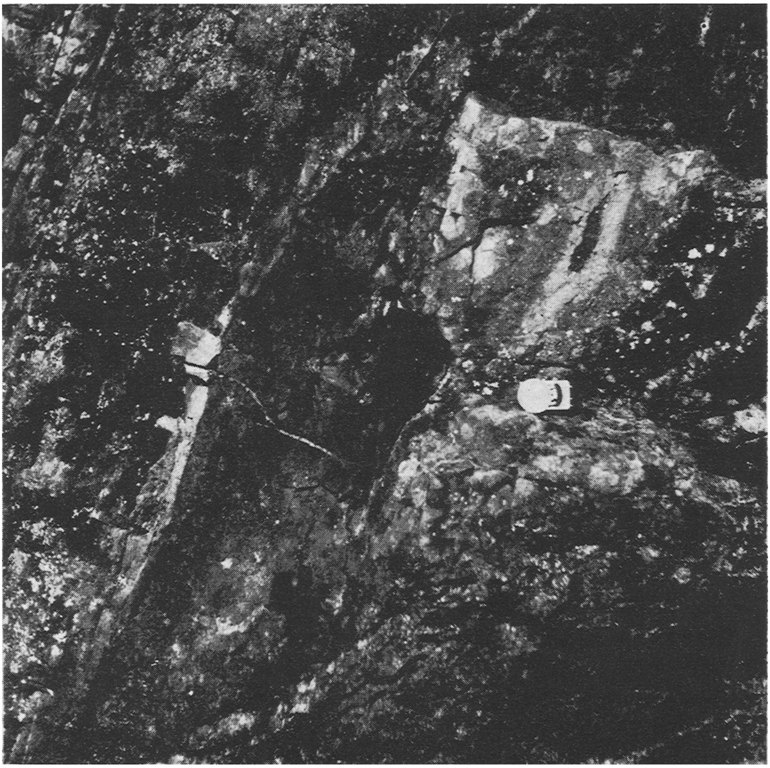

FIG. 1. Veining in arkoses at the contact on the south side of the Glenmore dolerite plug. The dolerite, showing good jointing, is on the left of the photograph. A zone of light-weathering arkose 2 cm. wide occurs between the dolerite and the black, smooth-weathering, fused arkose on the right, and from this zone a thin vein extends back into the fused arkose on the left of the exposure meter.

described by Ackermann and Walker (1960) from the contact of the Heilbron sill. The sharp boundary between the modified contact zone and the normal buchite indicates a very abrupt limit of reaction, which in any case was of very small extent considering the much greater width of the aureole of metamorphism and fusion of the arkoses.

It appears to be from this contact zone that the veins shown in fig. 1 penetrate back into the normal buchites farther away from the contact. The veins are up to 4 mm. wide and the longest extends 20 cm. into the normal buchite, but since the dolerite contact is oblique to the rock-face the true penetration of the veins is somewhat less than this. The contacts of the veins with the buchite are sharp and the rock splits easily along the contact, which often contains chloritic and limonitic alteration. The veins are composed of a felsitic groundmass containing skeletal alkali feldspar and hypersthene needles (fig. 2); embayed quartz grains and aggregates are included in this groundmass, and so far as can be seen are never continuous with the similar quartz grains of the adjacent buchite. There is, however, no sign of flow textures or of preferred orientation of the included quartz grains in the veins. Except for the presence of the hypersthene and the absence of the igneous-looking clinopyroxene and plagioclase the material of the veins resembles the arkose of the contact zone. The central 0·4 mm. width of every vein consists of microcrystalline quartz forming a veinlet, usually straight but locally sinuous and bifurcating, which sometimes intersects and slightly displaces the embayed quartz grains included in the vein.

The form of the veins and the sharpness of their contacts with the normal buchite suggest that they may be rheomorphic, originating from the felsitic rock of the contact zone; on the other hand, their inhomogeneous composition and the presence of the unoriented quartz grains might indicate formation by metasomatism or simply by devitrification of the glass of the normal buchite, along fractures that were subsequently filled with the microcrystalline quartz. In view of the discontinuity of the quartz grains of the veins and of the buchite, it seems likely that some mobilization and movement of the material of the veins has occurred, and it is probably correct to class them as rheomorphic, even though they may have moved only a short distance, metasomatism and devitrification possibly having been the principal processes in their formation. A chemical analysis of one of the veins is given under C in table II.

A very clear small-scale example of rheomorphic veining was found, however, very close to the contact with the dolerite, in a specimen of the thin pelitic horizon a few inches north-east of the main pelite described earlier. A vein of brown glass, 1·0 mm. wide, showing microspherulitic devitrification and containing green hypersthene microlites, intrudes

FIG. 2. A thin section of one of the veins shown in fig. 1. The vein, with felsitic texture, has a sharp contact against the glassy buchite at the top of the photograph, and the buchite is altered up to about 0·5 mm. from the contact. The veinlet of microcrystalline quartz in the centre of the vein cuts and displaces the two halves of a small embayed quartz grain just to the left of the middle of the lower half of the photograph. Ordinary light, × 16.

the pelitic band from the partly fused arkoses on either side (fig. 3). Residual quartz grains from the arkose have been strained off at the ends of the vein, but some of the smaller grains have been carried along with the liquid into the pelite. The rheomorphism displayed here is on a scale similar to the example described by Walker (1958) from the contact of a sill on the East Lomond, Fife.

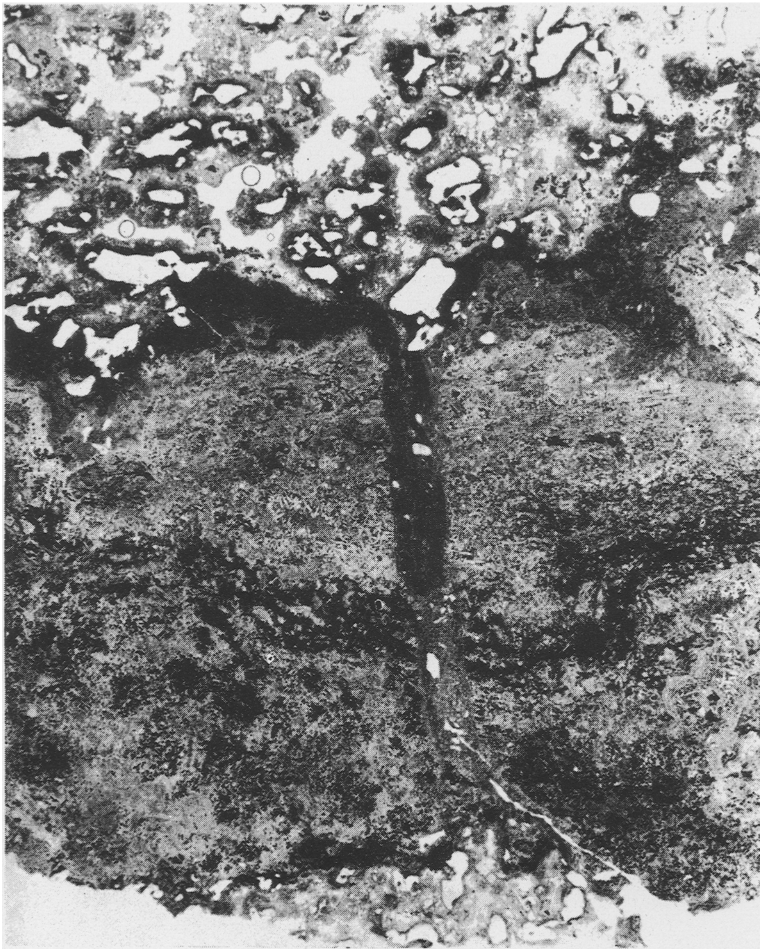

Fig. 3. A thin pelitic band cut by a rheomorphic vein of devitrified glass from the adjacent partly fused arkoses. Large residual quartz grains are strained off at the top end of the vein, and smaller grains carried into the pelite with the liquid in the vein. Ordinary light, × 6.

Yet another type of vein occurs in the analysed specimen, B, of the buchite 9 in. from the contact on the north-west side of the plug. The vein is 2·5 to 3·0 mm. wide; it has sharp contacts against the buchite and is clearly transgressive and of later date than the formation of the glass since it cuts across the embayed residual quartz and feldspar grains and the glass, which changes from colourless to brown within 0·5 mm. of the contacts of the vein. The vein consists of stumpy green clinopyroxene prisms 0·05 mm. long and skeletal alkali feldspar laths, sometimes showing a radiate arrangement, set in a deep brown glass with refractive index considerably less than that of canada balsam. This rock resembles the felsitic rock of the contact zone, and although the vein cannot be traced to a source in this zone it seems more than likely that it does represent mobilized material from this zone. The vein has not been included in the analysed portion of the rock.

Chemistry.

Two specimens of partly fused arkoses containing colourless glass of very fresh appearance were selected for chemical analysis. Both

TABLE II. Chemical analyses of thermally metamorphosed arkoses and their glasses, and a 'rheomorphic' vein.

	A, 3 ft. from contact.		B, 9 in. from contact.		C, Vein.
	Arkose.	Glass.	Arkose.	Glass.	
SiO_2 ...	70·15	70·42	74·44	71·60	73·12
TiO_2 ...	0·75	0·28	0·35	0·32	0·20
Al_2O_3 ...	13·24	12·54	11·71	12·14	10·66
Fe_2O_3 ...	1·90	0·89	1·14	0·79	4·34
FeO ...	1·43	0·67	0·85	0·80	0·68
MnO ...	0·03	0·03	0·02	0·02	tr.
MgO ...	1·08	0·52	0·75	0·62	0·88
CaO ...	2·58	0·96	1·98	0·79	1·92
Na_2O ...	2·88	3·29	2·97	3·68	2·59
K_2O ...	2·25	3·60	1·85	2·97	3·47
P_2O_5 ...	0·05	0·04	tr.	tr.	0·06
CO_2 ...	tr.	n.d.	0·03	0·00	tr.
H_2O^+ ...	3·03	6·43	3·86	6·07	1·54
H_2O^- ...	0·84	0·77	0·48	0·36	0·96
Total ...	100·21	100·44	100·43	100·16	100·42

New chemical analyses by B. C. M. Butler.

Modal composition of the arkoses

	A.	B.
Glass ...	40·7	55·2
Crystallites ...	2·6	1·0
Quartz ...	20·8	20·1
Feldspar ...	22·5	22·0
Opaques (mainly after mica)	13·4	1·7
Calcite ...	<0·1	—
	100·0	100·0
Refractive index of the glass (±·002)	1·496–1·500	1·499–1·502

specimens are from the north-west side of the plug; A was collected 3 ft., and B 9 in., from the contact. A sample of the glass was obtained from each rock by centrifugal separation with methylene iodide diluted with carbon tetrachloride; the glasses could not be obtained completely free from microlites, which form, however, only a very small proportion of the purified material. The arkoses and the glasses separated from them were chemically analysed and the results are given in table II.

TABLE III. Chemical analyses of thermally metamorphosed arkoses and their glasses, and a 'rheomorphic' vein.

(Recalculated anhydrous)

	A, 3 ft. from contact.		B, 9 in. from contact.		C, Vein.
	Arkose.	Glass.	Arkose.	Glass.	
SiO_2	72·82	75·53	77·46	76·40	74·68
TiO_2	0·78	0·30	0·36	0·34	0·20
Al_2O_3	13·74	13·45	12·19	12·95	10·89
Fe_2O_3	1·97	0·95	1·19	0·84	4·43
FeO	1·48	0·72	0·89	0·85	0·69
MnO	0·03	0·03	0·02	0·02	tr.
MgO	1·12	0·56	0·78	0·66	0·90
CaO	2·68	1·03	2·06	0·84	1·96
Na_2O	2·99	3·53	3·09	3·93	2·65
K_2O	2·34	3·86	1·93	3·17	3·54
P_2O_5	0·05	0·04	tr.	tr.	0·06
CO_2	tr.	n.d.	0·03	0·00	n.d.
	100·00	100·00	100·00	100·00	100·00
Normative composition					
Q	39·12	37·26	46·54	38·46	40·81
or	13·89	22·78	11·39	18·73	20·88
ab	25·18	29·90	26·17	33·25	22·40
an	13·33	5·01	10·21	4·18	7·38
C	1·43	1·63	1·28	1·52	—
en	2·81	1·41	1·94	1·65	1·52
of	—	—	0·05	0·29	—
di	—	—	—	—	1·53
mt	2·55	1·39	1·74	1·23	1·65
il	1·52	0·61	0·68	0·65	0·39
hm	0·16	—	—	—	3·30
ap	—	—	—	—	0·13
	99·99	99·99	100·00	99·96	99·99
Q+or+ab	78·19	89·94	84·10	90·44	84·09

A sample of the 'rheomorphic' vein shown in fig. 1 was obtained by cutting thin slabs from the unweathered interior of the rock and chipping the vein free from the adjacent buchite; the vein broke away easily along the contact with the buchite and thus it was easy to obtain a pure sample. The chemical analysis of the vein is given under C in table II. All the chemical analyses have been recalculated anhydrous, and are given, with the normative compositions, in table III.

The normative quartz and alkali feldspars of the buchites (A and B), the glasses, and the rheomorphic vein (C) are plotted on the triangular diagram $NaAlSi_3O_8$–$KAlSi_3O_8$–SiO_2 in fig. 4, with additional compara-

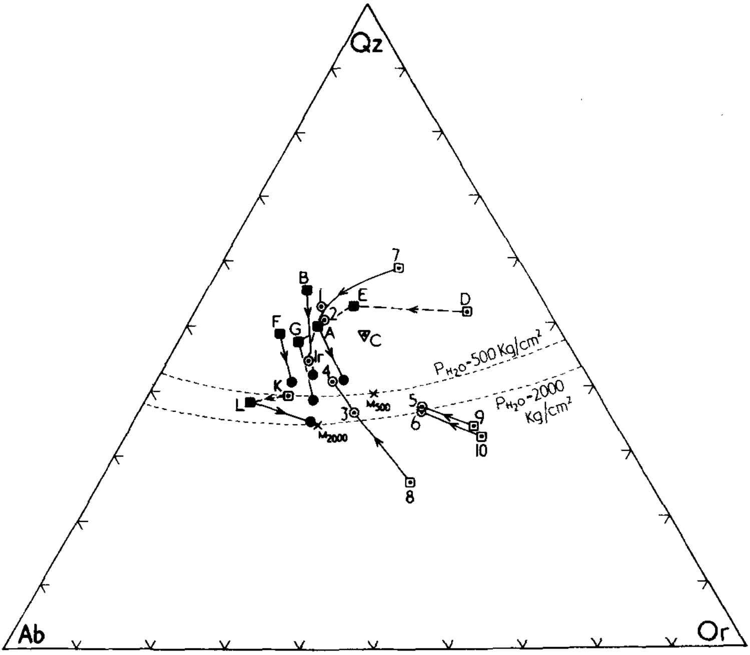

FIG. 4. Normative compositions of buchites, glasses, and associated rocks, plotted on the phase diagram $NaAlSi_3O_8$–$KAlSi_3O_8$–SiO_2. ⊡ unaltered parent rock; ■ buchite, connected by tie-line to ● glass separated from buchite; ⊙ palingenic dykes in the Satakunta diabase (Kahma, 1951); ▽ 'rheomorphic' vein in buchite of the Glenmore plug. The letters and numbers are explained in the text.

tive data. The cotectic boundary curves between the quartz and the feldspar fields are shown for pressures of water vapour of 500 and 2 000 Kg./cm². (Tuttle and Bowen, 1958, figs. 22 and 24), and the positions of the ternary minima on these curves are shown as M_{500} and M_{2000} (Tuttle and Bowen, 1958, fig. 38). The following additional points are plotted for comparison with the data for the Glenmore plug:

F and G represent two pairs of buchites and their glasses, 18 in. and

1 in. respectively away from the upper contact of a sill of Karroo dolerite intruded into arkose of the Middle Ecca Series (Permian) near Heilbron, Orange Free State; D represents the composition of the unmetamorphosed arkose, and E that of a buchite 4 ft. from the contact (Ackermann and Walker, 1960).

K represents the composition of the Green Valley tonalite (part of the Southern California batholith); L is the same rock, metamorphosed and partly fused, forming a large inclusion in a Tertiary andesite plug, and the composition of the glass separated from L is shown by the solid circle close to the position of the ternary minimum M_{2000} (Larsen and Switzer, 1939).

Points 1 to 10 and 1r represent the compositions of palingenic dykes and their parent rocks (granites and sandstone) associated with the pre-Cambrian Satakunta diabase in south-western Finland (Kahma, 1951, p. 32 and fig. 7—the analyses are numbered as in Kahma's paper).

The Glenmore analyses and tie-lines are very similar in position and trend to the data from the Heilbron sill, and indicate a similar mode of formation. The composition of each glass, relative to the parent rock, lies closer to the ternary minimum of the silica–alkali-feldspar system, and the formation of the glasses by fractional fusion of the lowest-melting composition from the parent rock is thus clearly indicated. The relative positions of the two Glenmore glasses in relation to the ternary minimum are as would be predicted from field and petrographic evidence; B comes from a locality closer to the contact with the dolerite than A, and the higher temperature of metamorphism of B is shown both by the higher modal percentage of glass in the rock (table II), and by the greater departure of the composition of the glass from the composition of the ternary minimum.

By contrast with the close approach of the glassy products of partial fusion of rocks to the low-temperature trough of the 'residual system of petrogenesis', the composition of the vein C lies at a considerably greater distance from the position of the ternary minimum. It was shown from the petrographic evidence (p. 875) that the vein might be either rheomorphic, derived from the contact zone of the buchite, or formed *in situ* by devitrification of the glass of the normal buchite, with or without addition of other constituents. In either case, the chemical analysis, C, represents the bulk composition of a rock comprising the fine-grained groundmass, the residual quartz grains contained in it, and the central veinlet of microcrystalline quartz; the composition is therefore silica-rich relative to the felsitic material, which represents the formerly liquid portion of the vein. The high Fe_2O_3 content of the analysis is probably due to the limonitic alteration along the contacts of the vein, which could not be excluded from the analysed material.

The palingenic dykes (nos. 3 to 6 in fig. 4) from granitic parent rocks associated with the Satakunta diabase lie close in composition to the ternary minimum of the Qz–Ab–Or system, indicating that there was partial or complete separation of the liquid from the partially re-fused granite. The palingenic dykes (nos. 1 and 2) from sandstone contain large rounded quartz and feldspar grains in the fine-grained micrographic groundmass, and these are interpreted by Kahma (1951, p. 32) as unmelted remnants of the original sandstone. The effect of these large grains was determined by calculation and subtracted from the rock composition to give the composition of the groundmass (1r), which represents the originally fused portion of the sandstone and lies close in composition to the ternary minimum.

Examples of rheomorphic veining have been described from the contacts of sills of Karroo dolerite, in association with which this phenomenon is particularly common (Walker and Poldervaart, 1949, p. 614). Chemical analyses of rheomorphic veins and mobilized sediments from sills of Karroo dolerite are given by Mountain (1944, 1960). The proportions of the normative Qz, Ab, and Or of these rocks appear to place them in two distinct groups; three of the analyses (Mountain, 1944, nos. I, II, III) fall within the silica field of the system Qz–Ab–Or, and may represent more or less unmodified sedimentary material, while four analyses (Mountain, 1944, no. IV, and 1960, nos. 1, 3, and 4) fall in or near the low-temperature trough extending from the position of the ternary minimum towards the eutectic point on the Ab–Or side of the triangle, and possibly represent sediments whose compositions have been altered by metasomatism. An analysis (Mountain, 1960, no. 2) of a granophyre associated with mobilized sediment no. 1 lies outside the trough on the Qz–Ab side. The compositions of these veins and mobilized sediments suggest that a variety of different processes may have been responsible for their formation.

Wager, Weedon, and Vincent (1953) show that the chemical composition of the Coire Uaigneich granophyre in Skye falls outside the range of normal granite compositions in the low-temperature trough of the Qz–Ab–Or system, and suggest that the granophyre may have been formed by the total fusion of quartz-rich material such as Torridonian arkose or acid Lewisian gneiss. If this is the correct inference to be drawn from the anomalous chemical composition of the granophyre, then it provides an extreme example of the complete melting and mobilization of country rock resulting in the intrusion of a large body of magma.

It is interesting to compare these products of mobilization, or presumed mobilization, with rocks that are considered to be the products of metasomatic transfusion associated with Karroo dolerite sills. Whereas the rheomorphic veins and mobilized sediments, to which reference was made above, differ markedly in composition from the composition of the ternary minimum in the Qz–Ab–Or system, five out of seven analyses of metasomatic granophyre produced by transfusion *in situ* of Karroo sediments (Walker and Poldervaart, 1949, Anals. 90, 92, 94, 95, 96) fall on the quartz–feldspar cotectic boundary line close to the position of the ternary minimum, even though the total Qz+Ab+Or is in no case greater than 80 % of the normative composition. These relations suggest that solid-liquid equilibria as well as metasomatism may have had some control over the compositions of the products of transfusion.

TABLE IV. Chemical analyses of normal and thermally metamorphosed pelites.

	H.	I.	J.
SiO_2 ...	57·74	54·30	54·43
TiO_2 ...	1·25	1·37	1·36
Al_2O_3 ...	17·50	21·23	19·80
Fe_2O_3 ...	1·75	4·06	3·60
FeO ...	5·42	3·45	4·73
MnO ...	0·09	0·09	0·09
MgO ...	2·39	1·71	2·19
CaO ...	3·06	1·46	2·22
Na_2O ...	1·50	1·49	1·20
K_2O ...	5·86	7·28	6·93
H_2O^+ ...	2·36	2·78	2·50
H_2O^- ...	0·06	0·96	0·90
P_2O_5 ...	0·22	0·21	0·19
CO_2 ...	1·27	0·07	0·13
Total ...	100·47	100·46	100·27

Modal analysis of H, and optical properties of the principal minerals.	Vol. %
Muscovite (γ 1·610)	29·4
Biotite (γ 1·650)	24·2
Epidote (β 1·734)	1·9
Garnet (n 1·797)	0·3
Plagioclase (An_{26})	7·5
Microcline	3·0
Quartz	30·4
Sphene	0·7
Carbonate	2·3
Apatite	0·3
	100·0

H. Normal Moine pelite 45 ft. south-east of the Glenmore plug.
I. Thermally metamorphosed pelite 3 ft. from the contact.
J. Thermally metamorphosed pelite 15 in. from the contact.
New chemical analyses by B. C. M. Butler.

Three specimens of the pelitic band metamorphosed by the Glenmore plug were chemically analysed; the results are given in table IV. The principal differences in composition between the normal and the thermally metamorphosed pelite are an increase in alumina and potash contents and in the Fe_2O_3:FeO ratio, and a decrease in silica, lime, and carbon dioxide; soda is nearly constant in amount, but possibly shows a slight decrease in the specimen closest to the dolerite contact.

Variation in alkali contents of thermally metamorphosed rocks. As mentioned earlier, the dolerite plug and the immediately adjacent metamorphosed Moine arkoses are surrounded on all sides by detritus, and consequently it is not possible to trace any individual band of fresh buchite from the contact with the dolerite into its unmetamorphosed equivalent farther away. (There is no doubt about the correlation of the pelitic horizon within and outside the metamorphic aureole, but unfortunately the glass of the arkose buchites close to the pelitic band is always altered.) In order to examine any possible changes in composition as a result of the contact alteration by the dolerite, a number of specimens of various types of normal Moine arkose were collected from exposures *in situ* within 100 yds. along the strike of the Moines to the south-east of the plug, and the alkali contents of five of these specimens were determined. The results of the analyses are shown in table V, with some comparative data.

The value of the molecular ratio Na/K is nearly constant in the five arkoses that have not been thermally metamorphosed (the average value for which is 1·11). There is a marked progressive increase in the Na/K ratio in the metamorphosed arkoses (reaching a value of 2·44 in the buchite 9 in. from the contact), which is due both to an increase of Na_2O and to a decrease of K_2O as the contact with the dolerite is approached. By contrast, the thermally metamorphosed pelites show a decrease in Na/K ratio compared with the same pelitic band outside the metamorphic aureole, and this decrease is due to an increase of K_2O. The variation of potash content of the pelites is rather larger than would be expected as a result of sedimentary variation over such a small distance, and the content of 7 % of potash in the thermally metamorphosed pelites is considerably higher than that of any other pelite in a series of twenty-two typical Moine schists that have been analysed from the Ardnamurchan area (B. C. M. Butler, unpublished data), the highest value for which was 6·1 % of potash. The normal pelitic and semi-pelitic schists show a wide range in Na/K ratio from 0·035 to 0·87, and a comparison of this ratio for the metamorphosed pelites with an average value for the Moine schists is not therefore particularly significant because of the wide variation in chemical composition of the latter, and because in the vicinity of the plug there are no other bands of pelitic rock which could be analysed for comparison.

From the data given in table V, it seems likely that the pelitic band

TABLE V. Alkali contents of some rocks from the vicinity of the Glenmore dolerite plug, and a comparison of certain quartzo-feldspathic rocks and their thermally metamorphosed equivalents.

		Weight %.		Molecular proportions.		Molecular ratio.
		Na_2O.	K_2O.	Na.	K.	Na/K.
Glenmore dolerite plug						
Dolerite at centre of plug		2·99	0·58	0·0482	0·0062	7·77
Dolerite 3 ft. from contact		2·68	0·55	0·0432	0·0058	7·45
Normal Moine arkoses: (1)		2·49	3·65	0·0402	0·0388	1·04
(2)		2·82	3·81	0·0455	0·0405	1·12
(3)		2·96	3·91	0·0478	0·0415	1·15
(4)		2·02	3·01	0·0326	0·0320	1·02
(5)		2·50	3·08	0·0403	0·0327	1·23
Average of normal Moine arkoses	Q.	2·56	3·49	0·0413	0·0370	1·11
Thermally metamorphosed arkoses (buchites)						
3 ft. from contact	A.	2·88	2·25	0·0465	0·0239	1·95
9 in. from contact	B.	2·97	1·85	0·0479	0·0196	2·44
'Rheomorphic' vein 4 in. from contact	C.	2·59	3·47	0·0418	0·0368	1·14
Buchite adjacent to vein		3·11	1·89	0·0502	0·0201	2·50
Normal Moine pelite	H.	1·50	5·86	0·0242	0·0623	0·39
Thermally metamorphosed pelites						
3 ft. from contact	I.	1·49	7·28	0·0240	0·0773	0·31
15 in. from contact	J.	1·20	6·93	0·0194	0·0736	0·26
Heilbron sill (Ackermann and Walker, 1960)						
Arkose 36 ft. from contact	D.	1·15	5·70	0·0186	0·0605	0·31
Buchite 4 ft. from contact	E.	2·75	3·20	0·0444	0·0340	1·31
Buchite 18 in. from contact	F.	3·75	1·85	0·0605	0·0196	3·09
Buchite 1 in. from contact	G.	3·50	2·30	0·0565	0·0244	2·32
Cerro de la Calaveras (Larsen and Switzer, 1939)						
Green Valley tonalite	K.	3·59	2·34	0·0579	0·0249	2·33
Partly fused tonalite in andesite	L.	3·92	1·69	0·0633	0·0179	3·54
Strontian (Guppy and Sabine, 1956)						
Tonalite	M.	4·48	2·87	0·0723	0·0305	2·37
Tonalite contact-altered by dolerite	N.	4·79	2·56	0·0773	0·0272	2·84
Ardmucknish (Flett, 1908)						
Phyllite 6 ft. from contact	O.	1·84	3·43	0·0297	0·0364	0·82
Buchite at contact with camptonite	P.	2·58	2·01	0·0416	0·0213	2·00
Soay (Wyllie, 1961)						
Average Torridonian arkose (from Kennedy, 1951)		2·45	3·35	0·0395	0·0356	1·11
Arkose xenolith in picrite sill		2·96	1·35	0·0478	0·0143	3·34
Flurrybridge (Reynolds, 1937)						
Newry granodiorite 15 yds. from contact with gabbro	R.	4·09	2·95	0·0660	0·0313	2·11
Granodiorite 10 yds. from contact	S.	3·90	3·82	0·0629	0·0406	1·55
Waterfoot (Reynolds, 1940)						
Triassic sandstone 9 ft. from contact with dolerite dyke		0·84	1·74	0·0136	0·0185	0·74
Sandstone 4 in. from contact		0·79	2·52	0·0127	0·0268	0·47
Mullaghbawn (Reynolds, 1941)						
Newry granodiorite 25 ft. from contact with gabbro	T.	4·41	2·95	0·0712	0·0313	2·27
Granodiorite 11 ft. from contact		3·22	3·80	0·0520	0·0403	1·29
Granodiorite 8 ft. from contact	U.	3·34	4·28	0·0539	0·0454	1·19
Granodiorite 2 ft. from contact		3·40	3·06	0·0549	0·0325	1·69
Granodiorite 2–3 in. from contact	V.	4·76	2·01	0·0768	0·0213	3·61
Langesundsfjord (Goldschmidt, 1914)						
Normal metamorphosed sandstone*	W.	0·89	1·79	0·0144	0·0190	0·76
Soda-rich metamorphosed sandstone*	X.	3·47	1·77	0·0560	0·0188	2·98
* CaO contents 4·86 % and 1·48 % respectively.						
Dinas Head (Agrell, 1939)						
Black carbonaceous slate (anal. 3)	Y.	0·51	4·57	0·0082	0·0485	0·17
Very fine-grained adinole (anal. 8)	Z.	8·89	0·31	0·1434	0·0033	43·5

gained potash, and the arkoses lost potash and gained soda in the metamorphic aureole of the plug. A possible explanation may be that there was an outward migration of potash from the buchites close to the contact, and that part of this potash was introduced into, and retained in, the adjacent pelitic band. The breakdown of muscovite and biotite in the metamorphosed pelite, and the formation of rims of potash feldspar between the micas and the quartz indicate reactions of the type:

$$\text{Muscovite}+\text{Quartz} = \text{Sanidine}+\text{Mullite}+H_2O,$$

$$\text{Aluminous biotite}+\text{Quartz} = \text{Sanidine}+\text{Spinel}+H_2O,$$

with a release of alumina (in the form of mullite and spinel) in excess of the amount required by the K_2O to form potash feldspar. Although the contents of both alumina and potash are higher in the metamorphosed than in the original pelite, there is a progressive decrease in the ratio Al_2O_3/K_2O (H, 2·99; I, 2·92; J, 2·86) which suggests that the excess of alumina was being used up in the pelites closer to the contact. This provides a possible mechanism for the fixing of part of the migrating potash in the pelitic band.

The alkali contents of the 'rheomorphic' vein, C, are very different from those of the normal buchite immediately adjacent to the vein, showing clearly that the vein cannot have been formed simply by devitrification of the glass of the normal buchite without change in chemical composition (cf. p. 875). The data do not, however, help to decide which of the other hypotheses of formation of the vein (by rheomorphism or by metasomatism along fractures) is likely to be correct. The alkali contents of the vein, C, are practically identical with the average alkali contents of the Moine arkoses, Q, outside the metamorphic aureole of the plug. In view of the marked changes of alkali content in the other rocks close to the contact with the dolerite, it is probable that this is a coincidence rather than that the vein represents the unmodified original composition of the arkoses at the contact, although it is hard to explain why the vein is potash-rich relative to both the adjacent buchites and the dolerite.

A comparison of the data for the Glenmore plug with other examples of metamorphism of quartzo-feldspathic rocks at the contacts with basic intrusions shows that movement of alkalis is very common or even ubiquitous in this type of environment. The data are summarized in table V and fig. 5. Instances of hybridization, granitization, and contact alteration in which there are important chemical changes in addition to variation in alkali contents have not been included, except for the special case of alkali metasomatism that culminates in the formation of adinoles (Agrell, 1939). Only those analyses are plotted in fig. 5 for which there is convincing evidence of change in alkali contents.

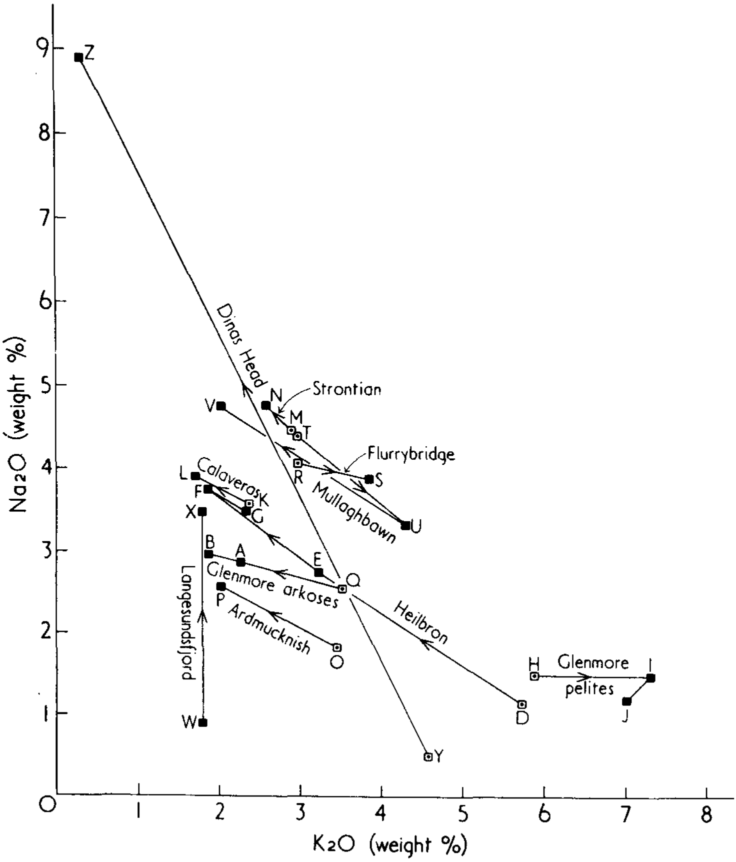

FIG. 5. Variations in alkali contents of quartzo-feldspathic rocks in thermal metamorphism. ⊡ unaltered parent rock; ■ thermally metamorphosed equivalent. The analyses are indicated by letters as in table V.

The metamorphism of arkose by the Heilbron sill (Ackermann and Walker, 1960) produces variations in the alkali contents analogous to those of the arkoses of the Glenmore plug, but with an even greater difference between the unmetamorphosed arkose and the buchite at the contact. A similar, but less extensive, variation is shown in the metamorphism of Green Valley tonalite by the Calaveras andesite (Larsen and Switzer, 1939), and of Strontian tonalite by a quartz-dolerite plug (Guppy and Sabine, 1956, p. 11). These two occurrences are of particular interest since each tonalite could be analysed both in the original and in the metamorphosed state. Although the original tonalites may have been of variable composition, the fact that the trend of variation is essentially the same in each case makes it more likely that the changes in the alkali contents are the result of the metamorphism.

The chemical analyses of phyllite and of the same rock metamorphosed and partly fused by a camptonite dyke at Ardmucknish (Flett, 1908) show changes in alkali contents similar to those in the examples given above. Flett noted that the phyllite buchite was richer in soda and poorer in potash than the unmodified phyllite, but considered that 'there seems no reason to believe that there has been any transfer of alkalis' during the metamorphism. In view of the similarity of this occurrence to the others already quoted, it seems likely that the changes noted by Flett are significant, and that transfer of alkalis has in fact occurred. The high soda contents of buchite xenoliths from the composite sill at Carsaig in Mull (Thomas, 1922) also suggest similar metasomatic changes, but the compositions of the original shales are not known.

Wyllie (1961) remarks that the fused xenolith in the picrite sill in Soay has a distinctly lower K_2O/Na_2O ratio than the average of three Torridonian arkoses given by Kennedy (1951), but that the Soay Torridonian rocks are known to vary in composition. However, the low K_2O content of the xenolith relative to the average (see table V) suggests that here too there has been movement of alkalis resulting in a slight gain of soda and a marked decrease of potash in the metamorphosed arkose.

The analyses of the palingenic dykes from sandstone associated with the Satakunta diabase (Kahma, 1951) also indicate that some transfer of alkalis may have occurred in the formation of the dykes. In fig. 1 there is a close similarity in trend of the points 7–1–2 for the Satakunta sandstone and dykes and D–E–F–G for the arkose and buchites from the Heilbron sill.

In every example quoted above there is a gain in soda and a loss in potash during metamorphism. It is worth noting that the decrease in the molecular proportion of the potash is not exactly balanced by the increase in the molecular proportion of the soda (i.e. there is not an ion-for-ion replacement), although in the metasomatism of the arkoses associated with the Heilbron sill this condition is nearly attained (cf.

table V, decrease in K from D to F = 0·0409, increase in Na = 0·0419). In all the examples fusion has occurred during the metamorphism, except in the case of the Strontian tonalite, although the separation of a lowest-melting composition represented by abundant micrographic intergrowths of quartz and alkali feldspar in the contact-altered rock (Guppy and Sabine, 1956, p. 11) may be the result of fractional melting. It appears probable that the alkali variation in these rocks is related to the formation of the glass.

The Glenmore arkoses are coarse-grained rocks containing two feldspars (microcline and sodic plagioclase) and mica. Although the plagioclase of the arkose will contain some potash feldspar in solid solution, and vice versa, fusion of such a rock would be expected to produce a mainly Qz–Ab liquid at quartz–plagioclase contacts and a mainly Qz–Or liquid at quartz–microcline or quartz–mica contacts. The liquid resulting from fusion of this kind would thus be inhomogeneous in composition. Yet staining of glassy Glenmore arkoses with sodium cobaltinitrite, using the method described by Chayes (1952), reveals no inhomogeneity of potash content of the glass, even though from the textural evidence (the parallel-sided channels of glass and the lack of alignment of microlites in them) it is clear that there has been virtually no movement of the glass or of the residual quartz and feldspar which could explain mechanical mixing. It is perhaps especially significant that the glass channels are of nearly constant width whether they are between quartz and feldspar or between quartz and relict mica (pl. XIX, fig. 2). One important effect of alkali metasomatism may thus be to homogenize the liquid once it is formed. But migration of chemical constituents may have an even more fundamental part to play in producing locally in the still solid rock a lowest-melting composition that is capable of being fused. A migration of soda to contacts of quartz with potash feldspar or mica or migration of potash to contacts of quartz with plagioclase will produce locally a composition much closer to the ternary minimum than that represented by the original phase boundaries, and it is possible that alkali migration of this kind is an essential precursor of fusion, without which melting may be difficult or impossible.

It would obviously be difficult to decide whether metasomatism preceded or followed fusion in any particular case, but two recently-described examples of the melting of rocks, one natural and the other experimental, are of particular interest. Ackermann and Walker (1960, p. 244) state that in the arkoses metamorphosed by the Heilbron sill 'the first glass is formed where grains of potash-feldspar and quartz come into contact with one another'. The original arkose was potash-rich (point D in fig. 4); the first-melting liquid may therefore have had a composition on the quartz–feldspar cotectic, but potash-rich for lack of available soda and because of the relatively gentle gradient out of the ternary minimum towards the Qz–Or side (cf. Tuttle and Bowen, 1958, fig. 40), and the liquid subsequently gained soda by metasomatism to attain a composition closer to the ternary minimum. Alternatively the soda metasomatism that is so well displayed in these rocks may have enabled the fusion to take place by adding potential albite to the quartz–potash feldspar boundaries in the solid rock, and the first product of melting may have had a composition close to that of the ternary minimum.

Winkler (1957) investigated experimentally the metamorphism of illitic clays and was able to reproduce anatectic melting at 700° to 720° C. The starting material was potash-rich, and consequently the product of melting 40 to 65 % of the initial material was a potash-rich composition at the Qz–Or end of the quartz–feldspar cotectic boundary. However, the products of melting 23 to 34 % of illitic clay with varying contents of NaCl and $CaCO_3$ had compositions very close to the liquid produced by melting of the clay alone (Winkler and von Platen, 1958, table 3 and fig. 6; 1960, table 7 and fig. 1), and the liquid attained a more sodic composition only at a higher temperature when 39 to 66 % of the original material had melted. The results appear to indicate that the added NaCl had little effect on the composition of the earlier products of melting, but reacted with the liquid after it was formed so as to give a composition closer to the ternary minimum. This would correspond to the case of metasomatism following fusion of natural rocks.

The evidence from the Glenmore plug also has a bearing on this problem. If the first product of fusion of natural rocks is potash-rich, as might be suggested from the evidence of the two papers just referred to, then the earliest appearance of glass should be seen at the contacts of quartz with the potash feldspar reaction rims round the original micas of the pelitic band. In fact, the arkoses, which contain both potash feldspar and sodic plagioclase, are the first to show signs of fusion, while the potash feldspar rims in the pelite are still apparently crystalline; the potash-rich pelite only shows extensive melting in the specimens from closest to the dolerite contact. These results confirm that in the fusion of natural rocks the first melting occurs when soda and potash are present in approximately equivalent proportions, thus agreeing with the data from the simple experimental system $NaAlSi_3O_8$–$KAlSi_3O_8$–SiO_2, but they do not show whether metasomatism precedes or follows fusion in this particular case.

The variations in alkali contents do not always directly aid the fusion, as is made clear in the example of melting of Green Valley tonalite (fig. 4). The effect of the metasomatism is to move the composition of the rock out of the low-temperature trough towards the Qz–Ab side, but the composition of the glass lies in the trough close to the ternary minimum for 2 000 Kg./cm.^{2} H_2O pressure. The opposite trends of the metasomatism and the fusion are well shown by the opposing directions of the tie-lines connecting K to L and L to its glass. The trend of metasomatism is probably related to the sodic environment of the xenolith in the andesite plug, a point which was noted by Reynolds (1941, p. 23 and fig. 6).

Examples of metamorphism in which there has been an increase of potash rather than soda have been described by Reynolds. At Flurrybridge in the Slieve Gullion area, Newry granodiorite has been metamorphosed by 'quartz-gabbro', and shows a marked increase in potash, while soda shows a slight decrease (Reynolds, 1937); the same relations are found in the metamorphism of a Triassic sandstone by a Tertiary dolerite dyke at Waterfoot, Co. Antrim (Reynolds, 1940), although in this case it is possible that sedimentary variation is the explanation for the differences between the unaltered and the metamorphosed sandstone. A more complex example of metamorphism of Newry granodiorite by a gabbro mass at Mullaghbawn (Reynolds, 1941) has resulted in a geochemical culmination of potash and depression of soda in the granodiorite at distances of 2 to 11 ft. from the contact, while at the contact itself there is a slight enrichment in soda and decrease in potash relative to the unmodified granodiorite. This is shown by the initial decrease and subsequent increase in the ratio Na/K as the contact is approached, and by the reversal of the trend of the tie-line connecting the points R, S, and T in fig. 5. The texture of the metamorphosed granodiorite figured by Reynolds (1937, plates 22 and 23; 1941, fig. 2 and plate 1) strongly resembles the parallel-sided glass channels produced by partial melting of igneous rocks (Knopf, 1938; Larsen and Switzer, 1939), but is ascribed by her to metasomatic replacement of the quartz grains of the granodiorite by felsitic material.

A more extreme example of metasomatism is the transfusion of quartz xenoliths in basic and ultrabasic potassic lavas described by Holmes (1936). In this case the added material entered the rock along sinuous channels of uniform width, usually following intergranular boundaries but sometimes traversing individual grains. The appearance of the transfused rock is similar to that of the fused Glenmore arkoses, except that the channels of glass occur everywhere between quartz grains (see Holmes, 1936, pl. XIII, fig. 3), whereas at Glenmore, and in every other case of partial fusion to which reference has been made here, the glass is always developed between quartz and feldspar or relict mica, and never between grains of the same species. The occurrence is of interest in that the formation of the glass must be ascribed largely to the introduction of potash, alumina, water, and other common rock-forming oxides from the enclosing magma, only the silica being contributed by the xenolith itself; the composition of the glass lies on the Qz–Or side of the ternary minimum of the Qz–Ab–Or system (see Wyllie, 1961, fig. 5), probably due to the highly potassic environment of the xenolith during the metasomatism.

It is interesting to compare these instances of metamorphism of quartzo-feldspathic rocks by basic igneous rocks with the example of metamorphism and metasomatism of quartzite by nepheline-syenite pegmatite in Langesundsfjord described by Goldschmidt (1914). Here there is a marked increase in Na_2O in the metasomatized quartzite, but at the expense of CaO, which shows an equivalent decrease, while K_2O is unaffected in amount.

The metasomatism of the pelitic band at the contact of the Glenmore plug is of an entirely different type from the extreme soda metasomatism of shale at dolerite contacts that results in the formation of adinoles (Agrell, 1939; Davies, 1956), although the Glenmore arkoses and several of the other examples of metamorphism of quartzo-feldspathic rocks show a trend of soda enrichment similar to but much less marked than that of adinolization. The contrasted metasomatic effects produced in the arkose and in the pelite at Glenmore afford an interesting example of selective diffusion of soda and potash between the contrasted rock types.

Water contents of the buchites and glasses. The H_2O^- contents quoted in table II for the buchites and their glasses were determined from the weight loss after heating a 1-g. sample at 105° C. for 1 hour. The weight losses of two samples (A and the glass from A) were also determined by reweighing after heating for repeated 10-minute intervals. It was found that both samples lost nearly all their 'H_2O^-' in the first 10 minutes, and thereafter both samples showed a steady slow loss in weight, which was continued even after heating for continuous periods of 16 and 19 hours at the same temperature. The overall loss of weight after a total of 42 hours' heating at 105° C. was equivalent to 1·3 % 'H_2O^-' in the buchite and 1·7 % in the glass; even after this time neither sample had reached constant weight. The results confirm the observations of Ross and Smith (1955, p. 1078) and Carmichael (1960, p. 326) that the loss of water is dependent more upon the duration than upon the temperature of heating.

The glasses of the buchites from Glenmore contain more than 6 % of H_2O^+ (H_2O retained after heating at 105° C. for 1 hour), which should correspond to a water vapour pressure, at the time of formation, of 2 000 Kg./cm.^{2} (Tuttle and Bowen, 1958, fig. 28), or a depth of about 7 km., which is almost certainly an over-estimate of the probable depth of cover at the time of intrusion of the plug. Comparable water contents (high H_2O^+ or H_2O^- or both) are found in many analyses of fused rocks and glasses (Flett, 1908; Thomas, 1922; Holmes, 1936; Larsen and Switzer, 1939; Frankel, 1950; Ackermann and Walker, 1960; Wyllie, 1961), and also in acid igneous glasses (Hawkes and Harwood, 1932; Tilley, 1957; Carmichael, 1960), and in residual glasses in tholeiites (Walker, 1935; Elliott, 1956).

Determination of the refractive-index:total-water-content relations of the glass of specimen A, following the method used by Ross and Smith (1955), gave the result:

Mean R.I. before heating (from table II)	(n_h)	= 1·498
Mean R.I. after heating	(n_e)	= 1·483
Total water content (from table II)	(w)	= 7·20%

$$(n_h - n_e)/w = 0{\cdot}015/7{\cdot}20 = 0{\cdot}0021$$

This value of the ratio is considerably less than any quoted by Ross and Smith, and indicates clearly that the glass is of perlite, not obsidian type, and that the water content represents water of hydration introduced later than the formation of the glass (perhaps even as a result of weathering), and not the water content of the liquid portion of the buchite at the time of metamorphism. Consequently the water content of the glass cannot be used to determine the temperature and pressure of metamorphism.

The ease with which synthetic silicate glasses of 'granitic' composition can be crystallized in the presence of water vapour under pressure, compared with the difficulty of crystallizing the same glasses under anhydrous conditions (cf. Tuttle and Bowen, 1958, pp. 5–6), suggests that natural silicate melts with a high water content would crystallize rather than vitrify on cooling. The preservation of clear isotropic glass with high water content in the Glenmore and other examples is therefore of interest. It is possible that the fused rocks originally had a low water content so that the conditions of solidification approached those of the anhydrous synthetic systems. More probably the vitrification is the result of quenching. The difference between the felsitic or granophyric texture and highly altered appearance of the metamorphosed arkoses of the majority of the dolerite plugs of Ardnamurchan and the fresh glassy buchites at Glenmore (cf. pl. XIX, figs. 1 and 2) is almost certainly related to the small size of the Glenmore plug. The wide metamorphic aureole indicates the continued flow of hot dolerite magma, but once the conduit became blocked, or the supply of magma ceased, cooling would be very fast due to the small heat content of the plug and the rapid dissipation of heat into the surrounding arkoses. The preservation of the glass and the absence of hydrothermal alteration in both the buchites and the dolerite is thus explained. The much larger size of the other dolerite plugs and dykes in Ardnamurchan allowed slower cooling, with crystallization of the liquid portion of the buchites and extensive alteration of the arkoses and the dolerite.

Conclusions.

The results of metamorphism of Moine arkoses by the Glenmore dolerite plug are essentially the same as those produced by fusion of Torridonian arkose in a picrite sill in Soay described by Wyllie (1961), who gives a full discussion of the conditions of metamorphism. Since the Glenmore rocks do not add any further information bearing on the problem of the temperature and pressure of metamorphism, it is not necessary to review all the data again here. It may be remarked that the presence of tridymite fringes round quartz grains in the buchites close to the dolerite contact permits only a restricted range of possible temperatures and pressures because of the small stability field of tridymite (Tuttle and England, 1955), provided it can be assumed that the tridymite was not formed metastably (cf. Wyllie, 1961, p. 24).

The wide metamorphic aureole around the plug and the absence of arkose xenoliths within it suggest that the dolerite was flowing over a considerable period of time. The lack of contortion of the quartzites, either on a large or on a small scale, is remarkable, considering that they were more than half liquefied; it seems probable that the liquid portion of the buchites was very viscous, and this would also explain the limited extent of the zone of hybridization, which is only 2 cm. wide. It is possible, however, that some reaction of the dolerite with the arkose took place, since olivine is apparently absent and small ovoid patches of felsitic material are present in the outer part of the plug; such reaction probably took place by assimilation of arkose, either stoped or dissolved from the sides of the plug. Solution of arkose can have had only a very small effect on the bulk composition of the dolerite, and the total volume of dolerite that flowed up the conduit must have been considerably greater than the volume of arkose that had to be removed to make room for it.

The product of partial fusion of the arkose is a buchite composed of 40 to 55 % of a glass with a composition close to the ternary minimum in the synthetic system $NaAlSi_3O_8$–$KAlSi_3O_8$–SiO_2, and the formation of the glass by fusion of the lowest-melting composition from the arkose is thus clearly indicated. In addition to the fusion, the arkoses show migration of alkalis resulting in a decrease of K_2O and an increase of Na_2O in the buchites close to the contact with the dolerite, while an associated pelitic band shows an increase of K_2O and a slight decrease of Na_2O. A review of other examples of thermal metamorphism of quartzo-feldspathic rocks by intrusions of basic magma shows that alkali metasomatism is a very common feature of this kind of occurrence, and it is suggested that local alkali migration is related to the fusion process.

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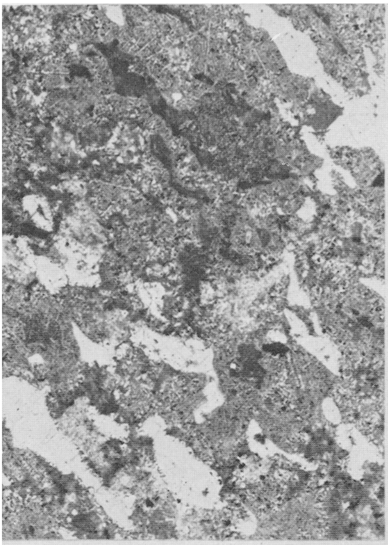
Explanation of Plate XIX.

Fig. 1. Thermally metamorphosed Moine arkose close to the contact on the south side of the dolerite plug at Camasinas, Ardnamurchan (Grid reference 656608). Embayed residual quartz grains are enclosed in a granophyric groundmass containing carbonate, apatite, and iron ore. The lath-shaped crystals in the groundmass extinguish in the same position as the adjacent quartz grains and possibly represent inverted tridymite. Magnification ×17. The rock is very similar in appearance to the metamorphosed Torridonian arkose figured by Wager, Weedon, and Vincent (1953, pl. XIII, fig. D).

Fig. 2. Partly fused Moine arkose 3 ft. from the contact of the Glenmore dolerite plug (analysed specimen A, table II). Parallel-sided channels of glass (mottled appearance) occur between quartz (white) and feldspar (grey) or original mica flakes (black). A feldspar grain partly recrystallized along cleavage cracks can be seen at the centre of the photograph. Magnification ×30.



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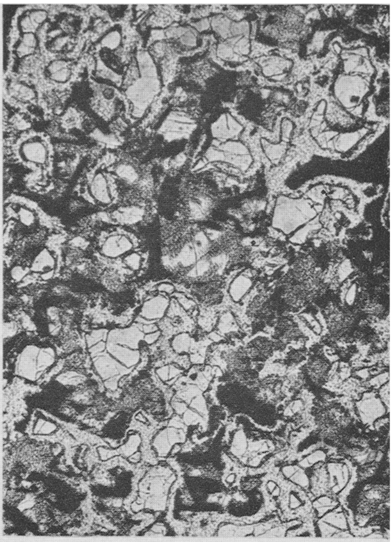

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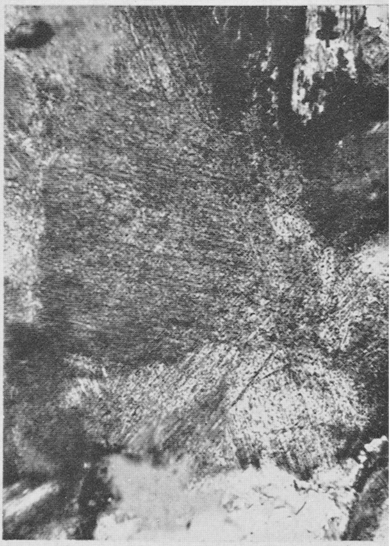

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FIG. 3. Thermally metamorphosed pelite (analysed specimen I, table IV). The relict schistosity can still be seen, but the micas are almost completely altered and reaction rims of potash feldspar occur between them and the quartz grains. Magnification × 30.

FIG. 4. A basal section of original muscovite in a thermally metamorphosed pelite 3 ft. from the contact with the dolerite. The fine needles are probably of mullite, in hexagonal arrangement relative to the original muscovite crystal. Magnification × 230.

All photographs in ordinary light.