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Spotted structures in gneiss and veins from Broken Hill, New South Wales, Australia

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SYNOPSIS

SPOTTED eye-like structures, made up of densely packed biotite 'pupils' mantled by quartz and feldspar, constitute about 10% by volume of a high-grade quartzofeldspathic gneiss located on the road to Purnamoota Homestead about 10 km north of Broken Hill. These spotted structures have an uneven distribution within rocks exposed at this locality. In some parts of the outcrop they tend to be closely spaced (fig. 1), whereas elsewhere they are less abundant and the spotted gneiss merges into an essentially homogeneous gneiss composed of quartz (34% by volume), plagioclase (24%), K-feldspar (17%), biotite (20%), and garnet, muscovite, and opaques (5%). This homogeneous gneiss is believed to have developed into a 'matrix' gneiss phase holding the 'eyes' which have a felsic mantle to mafic clot ratio of 4:1.

The whole eye-like structure appears to be a distorted prolate spheroid with its axis set close to the foliation plane of the gneiss. The internal biotite clot forms another prolate spheroid with its axis inclined at approximately 70° to that of the enveloping quartz-feldspar mantle. Although most of the eyes are isolated within the matrix, some are linked to hold three or four biotite aggregates (fig. S1) and rarely a vein-like patch which contains some ten or more partly linked spots of biotite may be found. In addition to the biotite, xenoblasts of almandine occur within some of the eye-like structures.

Whole-rock chemical analyses (including both major oxides and trace elements) show that the homogeneous gneiss and the spotted gneiss are very similar. The most notable feature of the geochemistry of the spotted rocks is the close chemical correspondence between the matrix and the whole eyes. Moreover, the compositions of corresponding minerals in these phases are very similar. For example, plagioclase is consistently about An_{35-40}, the biotites are all very iron-rich ($Fe/(Fe+Mg) \approx 0.87$) with compositions near siderophyllite, and K-feldspar has the composition $Or_{94}Ab_6$.

It has been suggested that the biotite spots formed by alteration of garnet probably during a retrograde metamorphic event. However, studies of the microstructure of the biotite and garnet in the spotted gneiss show that biotite of the spots does not replace garnet. Furthermore, the chemical similarity between the spots and the matrix is best explained by an isochemical rearrangement of components of the matrix phase to form the eyes. Thus, a more likely origin is best related to the displacement of matter along chemical potential gradients possibly induced by deformation in the rock system—a process described by the term metamorphic differentiation.

Veins in the Purnamoota Road gneiss are of two main contrasting types—regularly-disposed veinlets which are composed almost entirely of K-feldspar and quartz, and irregularly shaped discontinuous trondhjemitoid variants rich in biotite spots and carrying rare garnet porphyroblasts. The field relationship between these two main types of veins is difficult to discern. In some parts of the outcrop the veins occur adjacent to one another and locally appear to merge. Veins with modal (and chemical) compositions intermediate between the spotted and the K-feldspar-rich veins have also been recorded from the outcrop.

Despite a wide whole-rock chemical variation, the minerals in all the veins are similar chemically and compare closely with corresponding minerals

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* Professor E. R. Phillips died on 11th May 1980.

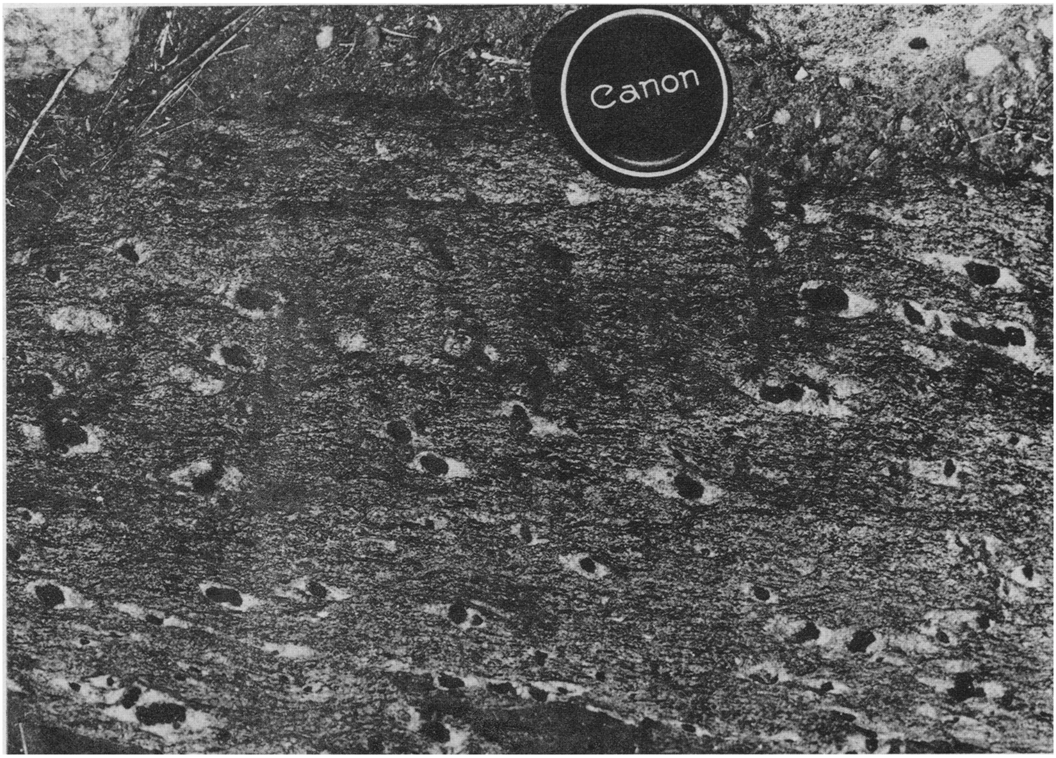

FIG. S1. A general view of the spotted Purnamoota Road gneiss. The eye-like form of the spots and mantles is evident. The white quartzofeldspathic portions are elongate parallel to the main foliation in the gneiss, whereas the elongate biotite 'pupils' tend to be arranged at angles of about 50–70° to the foliation. Most of the eyes contain one mafic spot but some have up to four closely associated biotite clots.

in the host gneiss. One exception may be the plagioclase in veins rich in K-feldspar where normative calculations indicate a composition near An_{14}.

Interpretation of the trace element data counts against the veins having formed by partial melting and the variable K-feldspar contents place both main vein types well away from ternary minima in the system Q–Ab–Or. Calculations based on the compositions of co-existing biotite and garnet in the host quartzofeldspathic gneiss and in associated prograde pelitic schists indicate an equilibrium temperature of 650° ± 50 °C at pressures between 3 and 4 kilobars. This fact, together with trace element data and the calcic nature of the plagioclase in the homogeneous gneiss and the matrix phase, places some doubt on the suggestion that partial melting has played a signficant role in the genesis of the veins.

Although mechanisms of vein formation such as igneous injection or metasomatism are considered as other alternatives for vein formation, we suggest that metamorphic segregation (as proposed for the origin of the spots in the gneiss) will also account for the development of the veins.

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SPOTTED STRUCTURES IN GNEISS AND VEINS FROM BROKEN HILL, NEW SOUTH WALES, AUSTRALIA

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QUARTZOFELDSPATHIC gneisses (or 'granite' gneisses) are abundant throughout the Willyama Complex of western New South Wales (Binns, 1964; Vernon, 1969; Chenhall et al., 1977). In the vicinity of Nine Mile Creek, about 6 to 11km north of Broken Hill, some of these exhibit an unusual, spotted, eye-like structure described by Andrews (1922), Browne (1922) and Chenhall et al. (1978). One of the best examples of this structure, together with related spotted and felsic veins, is seen in rocks located just east of the road to Purnamoota Homestead 2km NNE of the Nine Mile Mine (fig. 1; approximately grid reference 1773 000E 21238 000N on the Geological Map of the Broken Hill District published by the Australasian Institute of Mining and Metallurgy in 1968). The rocks from this area are known as the Purnamoota Road gneiss.

The 'eyes' consist of '... a dark centre or nucleus [of biotite], generally with subcircular outline, surrounded by an elongated area of white minerals, the whole simulating with startling clearness the appearance of a rather slit-like eye, so that the name "augen" gneiss is singularly appropriate...' (*Browne, 1922, p. 331*). These eyes are dispersed through a biotite gneiss host crossed by veins which may be grouped into two types — one containing biotite spots and tending to have a low K-feldspar content, the other usually being almost biotite-free but tending to be rich in K-feldspar. The distinctive spotted gneiss grades into a more even-grained, well-foliated but homogeneous 'platy' variant in which the spots are virtually absent. Both of these gneissic varieties display, to the east, a sharp, irregular contact with a leucocratic (biotite-poor or biotite-free) quartzofeldspathic gneiss containing numerous, apparently isolated 'pegmatitic' elongate patches (fig. 2). Sillimanite schists with incipient retrogression (Hobbs et al., 1968; Vernon, 1969; Chenhall, 1973) occur along the western contact of the quartzofeldspathic gneissic variants.

Browne (1922) suggested that the biotite spots within the eyes were derived by alteration of garnet. However, we note here the similarity of the eyes to stictolithic, fleck or 'cigar' structures described elsewhere (e.g. Loberg, 1963; Mehnert, 1968; Russell, 1969; Dahl, 1972; Fisher, 1973) and to diffusion spheres (Atherton, 1976), and the hypothesis that the eyes were derived by metamorphic differentiation is considered below. In addition, the association of such structures with quartzofeldspathic veins appears to be of fundamental importance (especially Loberg, 1963, p.102). Since the genesis of some quartzofeldspathic veins and leucosomes in migmatites is again in dispute (Ashworth, 1977, 1979; Yardley, 1977, 1979) or is the subject of detailed attention (e.g. Olsen, 1977; Yardley, 1978; also Hedge, 1972; Fershtater, 1977), we believe that the time is opportune to present an account of both the eye-like structures and the veins in the Purnamoota Road gneiss.

Descriptions

The 'homogeneous' phase of the Purnamoota Road gneiss

This is very similar in its mineralogy and chemistry to the spotted gneiss (into which it gradually changes) described below. In hand-specimen the homogeneous gneiss has an overall speckled grey colour, being composed mainly of quartz, feldspar and biotite — the latter showing a preferred orientation with individual flakes and aggregates of flakes imparting a foliation. Modal and chemical data appear in Table I, column 1.

In thin-section all the felsic grains are seen to be xenoblastic. The subhedral biotite flakes vary from 0.25 to 1mm in length (with some aggregates about 2mm long) whereas polygonal quartz crystals, which are commonly found in granoblastic aggregates 1 to 2mm across, range in size from about 0.25 to 0.5mm. The feldspars are similar in size to the quartz but some plagioclase grains are up to 2.0mm across. The plagioclase is unzoned andesine (An_{40} by optical determination; An_{35} from a chemical analysis, Table II, column 5), shows well-formed albite twins, and is commonly partially altered to muscovite. Some of it is locally antiperthitic and rare albite rims occur adjacent to K-feldspar. The K-feldspar ($Or_{94}Ab_6$, by chemical analysis, Table II, column 10) shows no perthitic structure under the microscope, but poorly-developed cross-hatched twinning and an undulatory extinction are evident. It is commonly free from turbid alteration products although some crystals are partially replaced by lobate blebs of myrmekite. The biotite has α = straw, $\beta = \gamma$ = deep brown and its chemical composition is given in Table II, column 1. Flakes of muscovite are found with the biotite or occur in matted aggregates between feldspar grains. Minor almandine, usually intergrown with muscovite, is present and accessory minerals include ilmenite (mainly in the biotite), zircon and apatite.

The spotted phase of the Purnamoota Road gneiss and associated veins

General. The rock type described in this section is a spotted, well-foliated gneiss in which the spots are eye-like, the margins having roughly a lens-shaped outline in most cross-sections normal to the foliation. The eyes, which from measurements on sawn surfaces constitute 10% of the whole rock, are composed of a central black portion of densely-packed biotite (and minor ilmenite) forming a core (or pupil) about which white felsic mantle domains are developed (fig. 3A). These eyes are set in a biotite gneiss matrix (or host) and they occur irregularly, some being close together or even merging, others being relatively far apart. An average chemical analysis of the whole spotted gneiss (matrix plus eyes) is listed in Table I, column 2. The gneiss contains quartzofeldspathic veins; those with biotite spots and tending to be low in K-feldspar are grouped together as vein type 1 whereas those low in or without biotite but tending to be rich in K-feldspar are designated as vein type 2. The matrix, the eyes, and the veins are described below.

The matrix or host. The gneissic host to the eyes is similar in mineralogy and microstructure to the homogeneous phase described above (Table I, column 3). Quartz, plagioclase and K-feldspar occur as xenoblastic grains varying in size from 2mm down to 0.1mm and subhedral biotite flakes and aggregates range from 0.25 to 2mm in length. Many felsic crystals vary from 0.5 to 1.0mm across, indicating a slightly coarser grain-size than for the homogeneous variety.

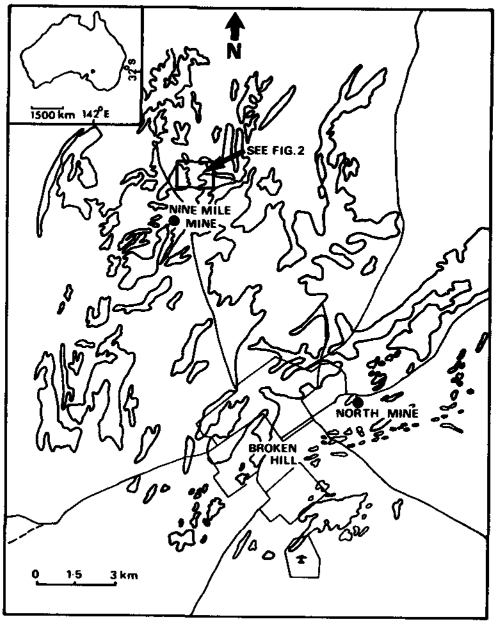


Fig. 1. Locality map showing major rock outcrops north of Broken Hill. After the Geological Map of the Broken Hill District, Australasian Institute of Mining & Metallurgy, 1968.

Quartz shows undulatory extinction and commonly occurs in aggregates of polygonal crystals. Most plagioclase grains (An_{38-42} by optical determination; An_{39} by chemical analysis, Table II, column 6) are almost unaltered and virtually unzoned with sharp, regular and persistent albite twins. Apparently non-perthitic K-feldspar shows incipient cross-hatched twinning and contains lobate myrmekite. It occurs in lesser amount than in the homogeneous gneiss. Strongly pleochroic biotite (α = straw, $\beta = \gamma$ = very dark brown; chemical analysis, Table II, column 2) is identical in colour and composition to that forming spots within the eyes. Almandine (Table II, columns 13-15) occurs as sporadic, individually roughly spherical crystals or as aggregates of grains 3 to 5mm in diameter. Most of the larger almandine xenoblasts contain numerous inclusions of quartz (0.1mm across) and rarer biotite flakes. Secondary muscovite (usually in the plagioclase) and accessory ilmenite complete the minerals of the matrix.

The eyes. The eyes are usually about 2cm long, 1 to 1.5cm deep and are sharply demarcated from the gneissic host. Further, the black biotite-rich centres of the eyes are very clearly separated from their biotite-free quartzofeldspathic mantles. Most eyes are isolated within the matrix but some are linked to *hold two or three biotite aggregates; uncommonly* a vein-like patch which contains some ten or more partly-linked clots of biotite is seen (fig. 3C).

The margin of the mantle appears to have the shape of a distorted prolate spheroid with its axis lying in or near the foliation plane (fig. 3A and D). Sections both close to an elliptical principal section and normal to the foliation have a roughly lenticular outline. Normal to such sections, within the foliation plane, the outline is more evenly elliptical and sections perpendicular to both of these are roughly circular. The form of the clots of biotite may be that of a prolate spheroid as well. The major axes of the black ellipses (as the clots appear in vertical sections) and the elongated closures of the whole eyes have acute angles varying from 54° to 72° with many close to 70°. This latter angle is taken to be close to the difference in direction between the two axes of the prolate spheroids. Optical examination of the orientation of the biotite flakes within the aggregates indicates that most flakes have their cleavages subparallel to the axis of the internal prolate spheroid.

Enlarged tracings and photostat copies of the eyes were made from over 50 sawn surfaces and the areas representing the dark mineral portions and the light mineral portions were cut out and weighed. In this analysis random sections across the foliation plane were used so that some sections represented a maximum content of biotite whereas other sections had no biotite. The biotite was found to constitute 19% of the eyes giving a ratio of light minerals : dark minerals of about 4:1 which is similar to that of the homogeneous gneiss and matrix. An average chemical analysis of a number of whole eyes appears in Table I, column 4.

The quartzofeldspathic mantles consist almost wholly of quartz, plagioclase and K-feldspar (Table I, column 5). Quartz grains, which locally tend to aggregate close to the biotite clots, are polygonal in shape and vary in size from 0.05 to 0.75mm; and the feldspars are of similar dimensions. The plagioclase (An_{39-42} by optical determination; An_{39} from a chemical analysis, Table II, column 7) has virtually the same composition *as that of plagioclase in the host and homogeneous* gneisses. Non-perthitic K-feldspar grains are irregularly distributed through some mantles, being sparsely developed in certain sections but clustering in other parts.

The 'pupils' of the eyes are composed almost entirely of subhedral densely-matted biotite flakes (0.2 to rarely 2.0mm in length) with a chemical composition (Table II, column 3) and pleochroic scheme the same as those of the biotites of the host gneiss and the homogeneous gneiss. Minor amounts of ilmenite (apparently in one or two anhedral grains about 1mm long) occur near the core of some pupils. Its chemical analysis appears in Table II, column 16. The ilmenite appears to be missing from many pupils but this may be the effect of random thin-section cuts. Rare subhedral muscovite flakes form the third mineral in the pupils.

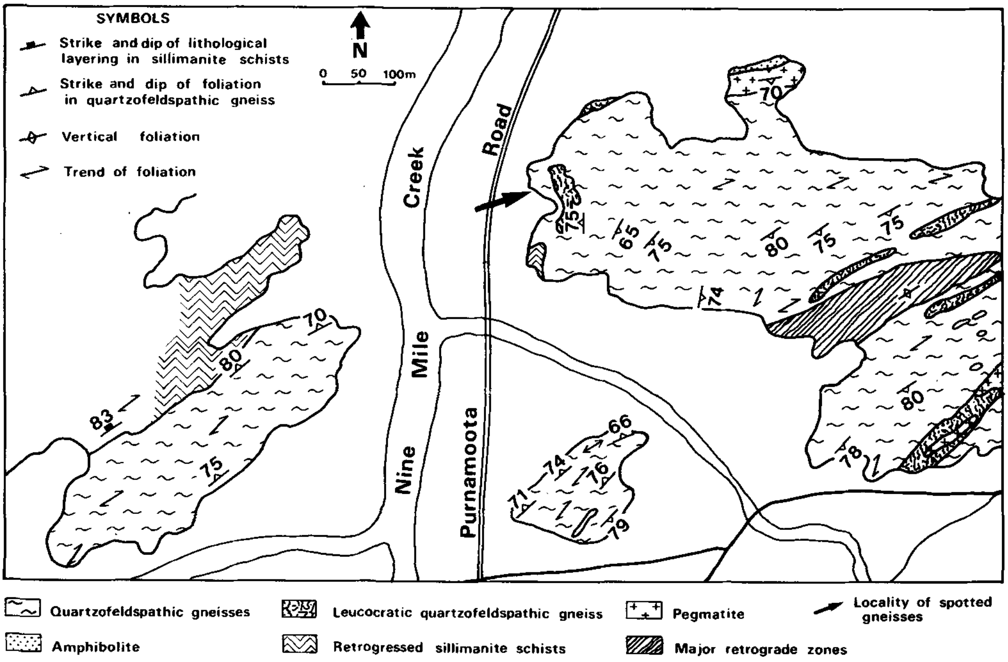


Fig. 2. Geological sketch map of the Nine Mile Creek area north of Broken Hill where the Purnamoota Road gneiss outcrops.

Almandine grains, morphologically and chemically identical to those found in the host gneiss, occur locally both in the felsic mantles or impinging onto the biotite clots. Rare isolated garnets may also be partly mantled by felsic domains. However, the roughly equidimensional habit of the almandines is markedly different in morphology from the elongate biotite pupils (fig. 4A and B). Also, the garnet is usually quite fresh and shows no alteration to biotite.

Vein type 1 with biotite spots. Veins composed essentially of quartz, plagioclase, K-feldspar and clots of biotite (fig. 3B, D and E) appear to be closely related to the eyes described above. This is especially so for those eyes linked together along the foliation plane to form composite vein-like patches (fig. 3C). In addition, apart from the comparable mineralogy in both developments, the similarity between the orientation of biotite clots in the veins and in nearby eyes suggests a close structural relationship (fig. 3D).

We can distinguish at least two subtypes of vein type 1: one (the more abundant rock) is almost free from K-feldspar and is a *trondhjemitoid* variant (Table I, column 6); and another (which appears to be spatially related to an example of vein type 2 described below, see fig. 3E) has quartz, plagioclase, K-feldspar and biotite all as essential minerals (also Table I, column 7).

Veins of the trondhjemitoid subtype have an irregular distribution and appear to be made up of the partial coalescence of irregular, apparently isolated, tapering vein-like felsic patches containing biotite clots; some of these patches look like aggregations of eyes and near their margins some veins seem either to merge with or to envelop eyes. For the most part, the veins run subparallel to the foliation and can be traced discontinuously over distances of 1 to 2m. Their width is irregular, varying from about 1cm up to 5cm. An example of the subtype richer in K-feldspar, illustrated in fig. 3E, has, however, a more regular form with almost parallel sides and a tabular disposition. It is also more even in width, varying from about 1 to 2cm across.

The biotite clots (Table II, column 4) have an irregular distribution within most veins and vary from ellipsoidal spots about 2mm across (which locally nest together in the trondhjemitoid subtype) up to blebs 1.5cm long. Many of them are between 3 and 10mm in length and the overall range in size in the trondhjemitoid variant is greater than that observed for biotite clots within the eyes. In general, it seems that the biotite spots in the subtype richer in K-feldspar are more regular in form but sparser in development than those in the trondhjemitoid veins. Virtually all the biotite associated with vein type 1 is present as dense spots and no mafic-rich selvages bordering these veins were seen (cf. White, 1966, fig. 3; Hedge, 1972, fig. 2; Olsen, 1977, fig. 3). Although it was not possible to do accurate micrometric analyses along the length of the veins, there can be little doubt that the proportion of felsic to mafic minerals in the veins is greater than that in the eyes.

Fig. 3A. Detail of the spotted Purnamoota Road gneiss showing the foliation and the elongation of the mantles and biotite spots. Rounded almandine porphyroblasts are present. The bar represents a length of 20mm.

Fig. 3B. Vein type 1, trondhjemitoid variant. Note the discontinuous nature and irregular width of the vein and the variability in size and disposition of the biotite spots. The direction of elongation of the biotite spots in the vein and in the enclosing gneiss is similar.

Fig. 3C. Elongate patches showing the extension of the white mantle along the foliation direction and around multiple biotite spots. Many of the biotite clots have a preferred orientation with their elongation set subparallel to that for the single spots illustrated near the bottom of the photograph.

Fig. 3D. Detail of vein type 1, trondhjemitoid variant. Although the vein is irregular in width its general conformity with the foliation in the spotted gneiss is evident. The subparallel nature of the elongation of all the biotite spots is well displayed. The bar represents a length of 10mm.

Fig. 3E. Veins type 1 and 2. The spotted vein is the subtype which contains K-feldspar as well as plagioclase, quartz and biotite. The vein type 2 (with virtually no biotite) is composed essentially of K-feldspar and quartz. It is almost ptygmatic in style. The dark, fine-grained areas are due to weathering and this has obscured part of vein type 2 and some of the spotting in the surrounding gneiss. The coin has a diameter of 18mm.

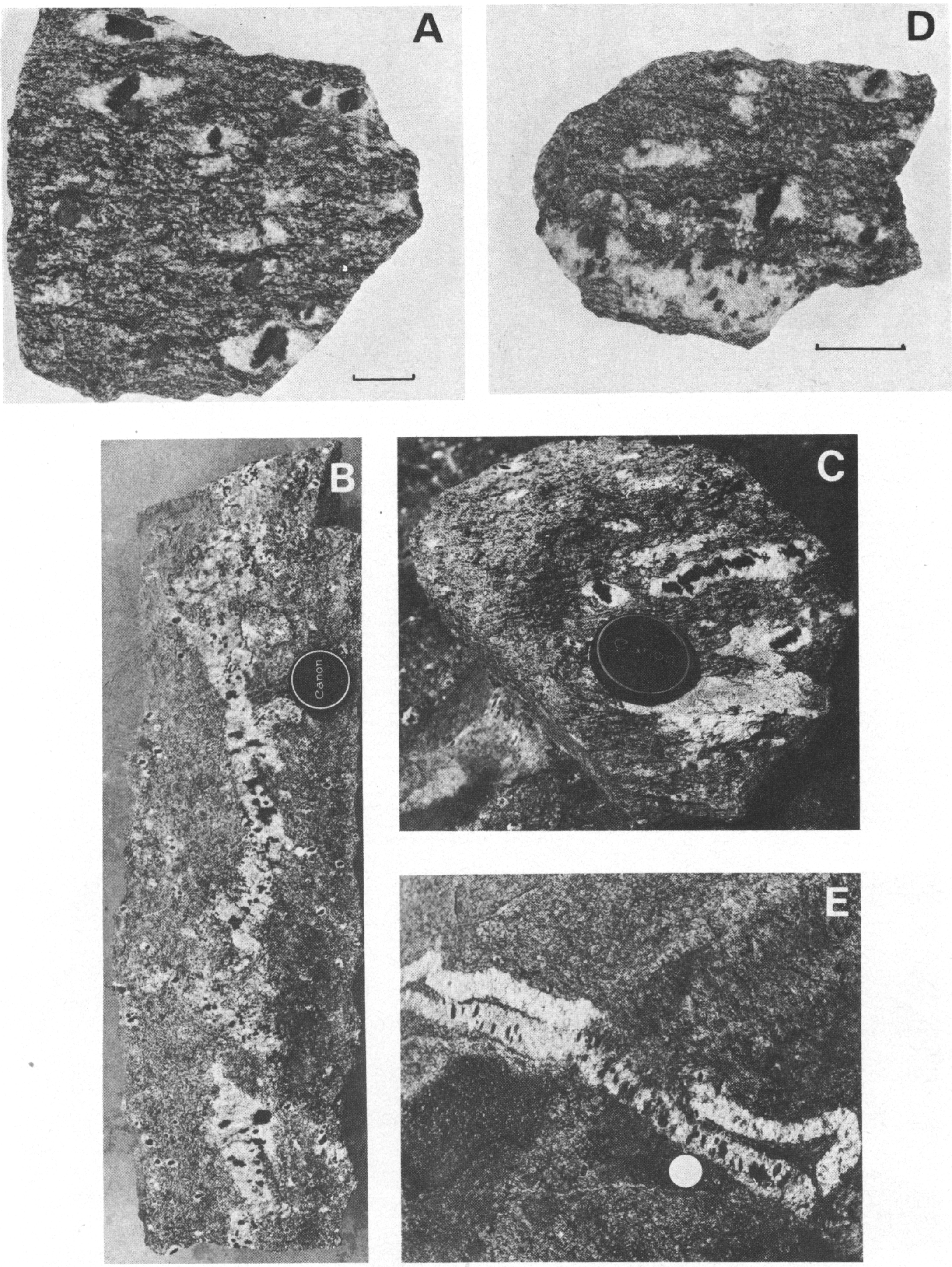
In thin-section, some parts of the veins (but not necessarily marginal portions) show a grain-size for the felsic minerals similar to, or only slightly larger than, that for the felsic minerals of the mantles or the matrix of the spotted gneiss. As the biotite of the clots is similar in grain-size as well, the close comparison to the eyes is most marked here. However, other parts of the veins (usually in the trondhjemitoid variant) show an increase in grain-size with both quartz and feldspar xenoblasts up to 3mm across. K-feldspar in veins of the second subtype commonly forms grains tending towards the larger size. Some of the smaller biotite clots are attenuated, appearing *to be compacted* between felsic grains; others have less definite margins with extensions of biotite splaying outwards into the quartz and feldspar. In addition, although subhedral muscovite flakes are present, ilmenite appears to be rarer than in the biotite clots of the eyes.

Throughout both subtypes, almandine grains may occur either within a biotite clot or adjacent to it and large isolated porphyroblasts of garnet (up to 10mm across) are locally well-developed in the trondhjemitoid variant. Optical measurements on the plagioclase (which is commonly slightly altered to sericite) gave a composition close to An_{40} (also Table II, column 8). Cross-hatched K-feldspar has the composition Or_{94} Ab_6 (Table II, column 11).

Vein type 2. Veins of this type are rich in quartz and feldspar: at one extreme, they are composed almost totally of K-feldspar and quartz (with minor muscovite and virtually accessory myrmekite and biotite, some forming rare clots, e.g. Table I, column 9); at the other, plagioclase is an additional important phase and biotite flakes are more abundant but are still only in minor amount (e.g. Table I, column 8). In form the veins rich in K-feldspar are usually quite regular; they have subparallel sides and can be traced continuously over distances of 2 to 3m or more. The vein illustrated in fig. 3E is about 2cm thick and locally shows an almost ptygmatic style of folding. It holds no discrete plagioclase grains (Table I, analysis 9). Another example is 3 to 4cm thick and strikes across the foliation, giving the appearance of a very narrow dyke. It carries more plagioclase, as may be discerned from its mode and chemical analysis (Table I, column 10). Vein type 2 may also form irregular patches or thin discontinuous veins within the host gneiss and it is such patches which usually (but not exclusively) *have significant* amounts of plagioclase. Locally, the K-feldspar-rich vein illustrated in fig. 3E has very thin biotite-enriched partial selvages but this property is not well-developed.

Thin-sections of the K-feldspar—quartz veins show that the grain-size is about 3 to 4mm and that all the crystals are xenoblastic. The cross-hatched twinned K-feldspar has a composition Or_{94} Ab_6 (Table II, column 12). Relatively coarse apatite is the accessory mineral. The 'dyke' represented by analysis 10, Table I, is slightly finer-grained and seemed regular enough in texture for the mode listed to be measured. The plagioclase in this rock is An_{37} from optical determinations; microprobe analysis of plagioclase in a discontinuous vein richer in plagioclase gave a composition close to An_{37} (Table II, column 9). However, plagioclase compositions suggested by norm calculations are more sodic (Table I, columns 8,9,10).

The detailed field relationship between vein types 1 and 2 is difficult to discern. Certainly, they may be quite separate in their development, but the association of the veins illustrated in fig. 3E, apart from strikingly demonstrating obvious differences such as the presence or absence of biotite clots, presents an additional problem. These two veins


A
D
B
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E

TABLE I. Modal and chemical data on the Purnamoota Road gneiss and related rocks.

	1	2	3	4	5	6	7	8	9	10	11	12
Modes (Vol.%)		*		*								
Quartz	34	34.8	35	33.2	41	-	-	-	-	34	38	27
Plagioclase	24	29.1	29	30.0	37	-	-	-	-	12	12	13
K-feldspar	17	12.4	12	16.2	20	-	-	-	-	43	28	49
Biotite	20	21.7	22	19.0	-	-	-	-	-	3	7	4
Muscovite	5	2.0	2	1.6	2					6	14	6
Garnet						-	-	-	-	2	-	-
Opaques etc.											1	1
Chemical analyses (Wt.%)												
SiO_2	67.84	68.41	68.10	69.17	74.32	67.40	72.76	73.33	72.12	73.57	72.25	72.64
TiO_2	0.73	0.70	0.73	0.75	0.03	0.38	0.31	0.23	0.06	0.10	0.27	0.08
Al_2O_3	13.98	14.12	14.03	13.93	14.24	16.03	13.47	13.92	14.34	14.14	14.50	14.03
Fe_2O_3	0.81	1.41	1.45	1.11	0.00	1.25	0.73	0.51	0.37	0.63	0.91	0.14
FeO	6.05	5.33	5.45	4.90	1.07	4.55	2.65	1.88	0.57	0.65	1.12	0.74
MnO	0.11	0.15	0.14	0.12	0.01	0.32	0.05	0.04	0.02	0.03	0.03	0.01
MgO	0.53	0.54	0.52	0.69	0.19	0.27	0.17	0.31	0.32	0.10	0.40	0.15
CaO	2.61	2.69	2.75	2.70	3.24	4.03	1.90	1.97	0.78	1.05	0.95	0.57
Na_2O	2.22	2.37	2.33	2.50	3.32	3.37	2.20	2.21	1.13	1.58	2.32	1.93
K_2O	3.86	3.35	3.30	3.40	2.64	1.51	4.61	4.69	9.42	7.26	6.36	8.68
P_2O_5	0.22	0.20	0.22	0.18	0.18	0.34	0.15	0.10	0.34	0.23	0.37	0.24
L.O.I.	0.58	0.64	0.73	0.76	0.62	0.47	0.81	0.77	0.60	0.83	0.84	0.90
Total	99.54	99.91	99.75	100.21	99.86	99.92	99.81	99.96	100.07	100.17	100.32	100.11
Barth mesonorms												
Q	34.06	35.25	35.41	34.80	36.39	32.60	37.11	36.88	27.25	33.31	31.62	26.13
Ab	20.83	22.12	21.82	23.21	30.44	31.10	20.46	20.47	10.37	14.58	21.27	17.68
An	12.03	12.52	12.73	12.63	15.22	18.33	8.75	9.41	1.68	3.81	2.34	1.29
Or	13.31	10.50	10.16	11.74	14.06	0.95	23.59	24.68	54.97	42.18	35.12	50.90
Bi	16.82	16.11	16.28	14.43	2.99	13.14	7.39	6.25	3.04	3.03	5.20	2.27
Il	0.27	0.59	0.68	0.92	0.00	0.50	0.38	0.00	0.09	0.00	0.36	0.11
Ap	0.48	0.43	0.48	0.39	0.38	0.71	0.32	0.22	0.73	0.49	0.79	0.51
C	2.20	2.48	2.45	1.87	0.51	2.60	2.00	2.10	1.88	2.61	3.30	1.11
Normative An/(Ab + An)	36.6	36.1	36.9	35.3	33.3	37.1	30.0	31.5	13.8	20.7	9.9	6.8
Trace element analyses (ppm)**												
Y	63	68	72	56	-	102	-	-	12	21	13	7
Sr	216	181	174	183	-	267	-	-	303	216	100	139
Zr	243	233	250	189	-	104	-	-	<2	32	140	25
U	4	3	3	6	-	2	-	-	2	9	65	24
Rb	194	183	178	181	-	102	-	-	216	206	348	360
Th	23	25	24	19	-	13	-	-	4	7	24	5
Pb	32	34	34	35	-	37	-	-	110	93	114	130
Ga	21	20	20	20	-	22	-	-	13	15	18	13
Zn	111	104	106	99	-	81	-	-	7	19	89	19
Cu	20	44	<10	176	-	75	-	-	17	10	<10	<10
Ni	<10	<10	<10	<10	-	<10	-	-	<10	<10	<10	<10
Mn	795	1025	996	992	-	2022	-	-	60	208	227	68
Cr	197	198	193	269	-	226	-	-	184	191	134	199
V	28	31	33	35	-	17	-	-	5	7	13	9
Ti	4885	4755	4929	4901	-	2280	-	-	184	638	1975	536
Ba	622	622	541	699	-	375	-	-	2629	1225	319	484

1. 'Homogeneous' phase of the Purnamoota Road gneiss (average of 2).
2. Whole spotted Purnamoota Road gneiss (average of 3).
3. Matrix of the Purnamoota Road gneiss (average of 2).
4. Whole 'eye' in the Purnamoota Road gneiss (average of 2).
5. 'White' of 'eye' in the Purnamoota Road gneiss (average of 2).
6. Vein type 1 (plagioclase-rich essentially K-feldspar-free veins with quartz and biotite spots) occurring in the Purnamoota Road gneiss (average of 2).
7. Vein type 1 (veins containing plagioclase, K-feldspar, quartz and with biotite spots) occurring in the Purnamoota Road gneiss.
8. Vein type 2 (veins containing plagioclase, K-feldspar, quartz and some biotite but not as spots) occurring in the Purnamoota Road gneiss.
9. Vein type 2 (veins rich in K-feldspar with quartz but almost biotite-free) occurring in the Purnamoota Road gneiss (average of 2).
10. Another example of vein type 2 (the 'dyke') with low plagioclase occurring in the Purnamoota Road gneiss.
11. Leucocratic quartzofeldspathic gneiss occurring adjacent to the Purnamoota Road gneiss.
12. 'Pegmatitic' elongate pod occurring within the leucocratic gneiss (no. 11).

* Calculated

** The trace element analyses were obtained from only one sample of each rock type.

Analysts: R.H. Flood and S.E. Shaw, Macquarie University.

locally coalesce as a somewhat irregular patch of vein material. Although the identity of both vein types could be recognized in some of this patch, our overall impression was that they essentially merged.

Rocks associated with the Purnamoota Road gneiss

As noted in the introduction, a leucocratic gneiss with its associated 'pegmatites' has a sharp easterly contact with the Purnamoota Road gneiss. Neither the leucogneiss nor its enclosed 'pegmatites' exhibit spotting and mapping indicates that they have not influenced the development of eyes in the Purnamoota Road gneiss. Both leucogneiss and pegmatites stop abruptly at the contact with the Purnamoota Road gneiss (and may even predate it), and no field connection between the eyes and the contact is evident. Chemical and modal data on these two rock types are included in Table I (columns 11 and 12) mainly for comparative purposes. It will become evident from the discussion below that such rocks need play no part in a metamorphic segregation model for the genesis of vein type 1. Field relations count against them forming anatectic melts which introduced vein type 2 material into the Purnamoota Road gneiss, although the possibility of the derivation of 'pegmatite' from its host leucogneiss by partial melting is not denied.

Chemical and modal data

Major element analyses (Table I) show that the homogeneous phase of the Purnamoota Road gneiss, the whole spotted gneiss, the matrix and the whole eyes are virtually identical apart from slight variation in SiO , CaO, Na_2O and, to a lesser extent, K_2O. Moreover, their trace element geochemistry is also very similar. Values for Rb/Sr lie in the range 0.90-1.02 with Rb x 10^3/K, 6.05-6.58; Ba/Rb, 3.04-3.86 and Ba/Sr, 2.88-3.82. Compositional variation in the veins is a consequence of the modal criteria by which the vein types were defined.

For these veins, it may be noted that trace element analyses of the trondhjemitoid subtype show that Y, Sr, Cu, Mn and Ba are greater than, and Zr and Rb less than, those elements in the host. Pb, Ga, Zn and V are present in approximately similar amounts. The K-feldspar-rich subtype of vein type 2 has Sr, Pb and Ba greater than, and Y, Zr, Zn and Ti less than, these elements in their enclosing gneiss. Rb, Ga and Cu values are quite similar.

Modal and normative data indicate that the K-feldspar content of the homogeneous gneiss is greater than that of the spotted gneiss, the matrix and the whole eyes, with plagioclase exhibiting a reverse relationship. Normative and modal biotite contents remain fairly constant throughout, although biotite is possibly more abundant in the matrix of the spotted gneiss. A sympathetic relationship between K-feldspar and plagioclase is also evident between the two vein types exhibiting extreme compositional differences. In both, mesonorm biotite contents are diminished relative to the enclosing spotted gneiss.

Consideration of the mineral analyses (Table II) leads to the observation that all the biotites are Fe-rich (near siderophyllite) with molar FeO/(FeO + MgO) greater than 0.84. In particular, very close agreement exists between the compositions of biotite from the eyes and from the matrix of the spotted gneiss. Molar distribution coefficients (Kretz, 1959), $K_{D(Fe-Mg)}^{\text{biotite matrix-spots}}$ are close to 1.

In general, there is good agreement between compositions of plagioclases determined by microprobe and by optical methods and these also generally correspond with normative plagioclase compositions calculated from the whole rock analyses (Table I). The disparity evident for the An/(Ab + An) values in analyses 8-10, Table I, (examples of vein type 2) as compared with measured plagioclase compositions of about An_{37} can be explained by the cross-association of normative Ab contained in the usually abundant K-feldspar with the minor normative An held in the relatively low amounts of modal plagioclase.

Almandines from the homogeneous and spotted gneiss phases are interesting because they exhibit a marked degree of compositional diversity not only between grains in the one rock sample but also within individual grains. This chemical variation is expressed in terms of difference in Fe, Ca and Mn contents and individual crystals appear to have an irregular, patchy 'zoning' (cf. Chenhall, 1976). The 'zoning' has not yet been examined in any detail.

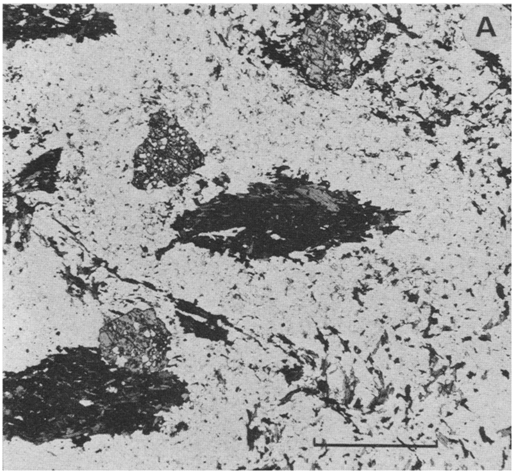

Fig. 4A. Photomicrograph of the spots, mantle and some matrix, showing, in particular, the elongation of the central spots (composed of densely-matted biotite flakes, many of which are arranged subparallel to the spot elongation) as opposed to the rounded equidimensional habit of the almandine crystals. Garnet grains occur in part of the central spot (bottom-left), within a mantle and in the matrix (top-right) in a random manner, showing that they are independent of spots, mantle and matrix in spatial distribution. The garnets appear to be unaltered. Plane-polarized light. The bar represents a length of 5mm.

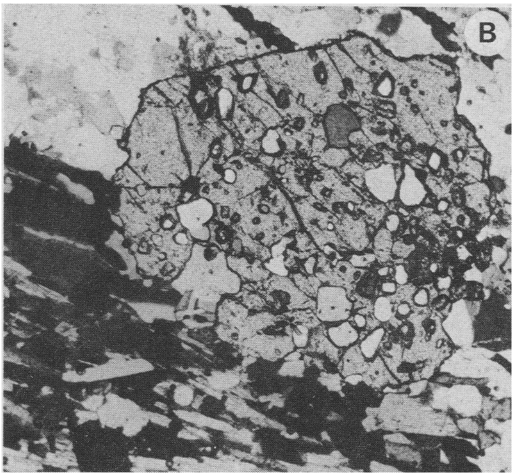

Fig. 4B. Detail of the bottom-left area of Fig. 4A showing subhedral porphyroblastic garnet which is unaltered and the preferred orientation displayed by the biotite flakes in the spots. Partly crossed nicols.

Table II. Electron-microprobe analyses of minerals in the Purnamoota Road gneiss and related rocks.

	Biotite				Plagioclase				K-feldspar				Garnet			Ilmenite	
Wt%	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	
SiO_2	33.40	32.25	32.26	33.56	59.44	57.60	57.82	59.03	58.53	64.32	64.82	64.12	35.54	35.41	35.59	-	SiO_2
TiO_2	2.74	2.53	2.50	3.04												49.16	TiO_2
Al_2O_3	17.89	17.46	17.31	17.77	26.62	26.88	27.07	27.02	25.69	18.85	18.93	18.80	20.74	20.63	20.67	0.16	Al_2O_3
FeO*	30.91	30.17	30.24	30.04									37.21	32.39	31.72	46.53	FeO*
MnO	0.25	0.30	-	-									4.16	4.15	3.80	1.40	MnO
MgO	2.62	2.77	2.85	2.28									0.74	0.59	0.64	0.25	MgO
CaO					7.52	8.14	8.23	7.66	7.96				2.02	5.78	7.20		CaO
Na_2O	0.29	0.36	0.44	0.24	7.62	7.12	6.95	7.40	7.26	0.62	0.72	0.65					Na_2O
K_2O	9.45	9.14	9.16	9.33	0.28	0.25	0.19	0.22	0.20	16.02	15.99	16.08					K_2O
TOTAL	97.55	94.98	94.76	96.26	101.48	99.99	100.26	101.33	99.63	99.81	100.46	99.65	100.41	98.95	99.62	97.50	

* Total Fe as FeO

Number of Ions on the basis of	22 Oxygens				32 Oxygens				32 Oxygens				12 Oxygens			6 Oxygens	
Si	5.29	5.26	5.27	5.36	10.48	10.33	10.33	10.42	10.51	11.91	11.92	11.90	2.93	2.93	2.93		Si
Al^{iv}	2.71] 8.0	2.74] 8.0	2.73] 8.0	2.64] 8.0	1.52] 12.0	1.67] 12.0	1.67] 12.0	1.58] 12.0	1.49] 12.0	0.09] 12.0	0.08] 12.0	0.10] 12.0	0.07] 3.0	0.07] 3.0	0.08] 3.0		Al^{iv}
Al^{vi}	0.63	0.62	0.60	0.70	4.01	4.01	4.03	4.04	3.95	4.03	4.02	4.01	1.94	1.94	1.92	0.01	Al^{vi}
Ti	0.33	0.31	0.31	0.36												1.93	Ti
Fe^{2+}	4.10] 5.71	4.11] 5.75	4.13] 5.73	4.01] 5.61									2.56	2.24	2.18	2.04	Fe^{2+}
Mn	0.03	0.04	-	-									0.29	0.29	0.26	0.06	Mn
Mg	0.62	0.67	0.69	0.54									0.09] 3.12	0.07] 3.11	0.08] 3.15	0.02	Mg
Ca	-	-	-	-	1.42	1.56	1.57	1.45	1.53				0.18	0.51	0.63		Ca
Na	0.09	0.11	0.14	0.07	2.60] 4.08	2.47] 4.09	2.41] 4.02	2.53] 4.03	2.53] 4.11	0.22	0.26	0.23					Na
K	1.91] 2.00	1.90] 2.01	1.91] 2.05	1.90] 1.97	0.06	0.06	0.04	0.05	0.05	3.79] 4.01	3.75] 4.01	3.81] 4.04					K
Or Mol%					1.54	1.40	1.08	1.23	1.12	94.45	93.60	94.21					
Ab					63.71	60.43	59.80	62.83	61.60	5.55	6.40	5.79					
An					34.75	39.17	39.12	35.94	37.28	-	-	-					

1. From the 'homogeneous' phase of the Purnamoota Road gneiss.
2. From the matrix of the Purnamoota Road gneiss (average of 4).
3. From 'eyes' in the Purnamoota Road gneiss (average of 5).
4. From vein type 1 (veins with biotite spots) occurring in the Purnamoota Road gneiss (average of 2).
5. From the 'homogeneous' phase of the Purnamoota Road gneiss.
6. From the matrix of the Purnamoota Road gneiss (average of 3).
7. From 'eyes' in the Purnamoota Road gneiss (average of 2).
8. From vein type 1 occurring in the Purnamoota Road gneiss.
9. From vein type 2 occurring in the Purnamoota Road gneiss.
10. From the 'homogeneous' phase of the Purnamoota Road gneiss.
11. From vein type 1 occurring in the Purnamoota Road gneiss.
12. From vein type 2 (veins rich in K-feldspar but almost biotite-free) occurring in the Purnamoota Road gneiss.
13. 14, and 15. Analyses of one garnet in the matrix of the Purnamoota Road gneiss illustrating its variable composition.
16. From a 'pupil' in an 'eye' in the Purnamoota Road gneiss.

Analysts, N. Ware (Australian National University) and B.E. Chenhall, using a TPD electron microprobe incorporating an automatic energy dispersive, analysis and detection system (see Reed and Ware, 1973).

K-feldspar in all samples is very low in Na and this accounts for its apparent non-perthitic nature.

Discussion

The origin of the eyes in the Purnamoota Road gneiss

It has been suggested that the biotite in the eyes of the Purnamoota Road gneiss formed by pseudomorphous replacement of almandine during subsequent alteration (Browne, 1922, p. 331). Notwithstanding that the formation of the quartzofeldspathic portions of the eyes is not readily explained by alteration, the following microstructural features indicate that the biotite spots do not replace garnet:

(a) unaltered, equant almandine occurs adjacent to elongate biotite clots showing that neither mineral replaces the other and that the outline of the spots and the almandine crystals have a completely different morphology (fig. 4); and

(b) essentially unaltered almandines, with the same morphology as those associated with the biotite in the spots, occur randomly dispersed throughout both the matrix of the host gneiss (clearly without quartzofeldspathic mantles) and in the mantles of the eyes. If the biotite were formed by alteration of garnet during retrogression, matrix garnets should also be affected, producing some unmantled biotite spots. These have not been found. (A similar independence in microstructure between garnet and biotite spots is seen in type 1 veins, again suggesting no retrograde connection between these two minerals.)

There is no microscopic evidence for the former presence of cordierite in the Purnamoota Road gneiss and tourmaline, andalusite and sillimanite have not been observed in these rocks. Hence, both the proposal of Russell (1969) that the formation of flecks in gneisses from the Vastervik area was due to the porphyroblastic growth of cordierite, followed by the breakdown of this mineral to give biotite and muscovite or andalusite and sillimanite, and the subsequent hypothesis of Dahl (1972) that the existence of either muscovite or andalusite-sillimanite in the same rocks depends on vapour fugacity or pH cannot be applied to the Purnamoota Road gneiss.

An additional fact makes it unlikely that biotite in the clots is of retrograde origin. This is that all the biotites (including those in the homogeneous and matrix phases) are very similar chemically and presumably formed during the same prograde metamorphic episode.

As pointed out above, the composition of the homogeneous gneiss is similar to that of the spotted gneiss, but small differences in the proportions of K_2O, Na_2O and CaO reflect differing K-feldspar to plagioclase ratios. Of greater importance is the observation that chemical analyses of the eyes themselves are in close agreement with analyses of the matrix and of the whole spotted gneiss. Noting these differences, the homogeneous phase appears to be a likely parent at least for the development of the eyes and the matrix. It is conceivable that the veins within the spotted gneiss, because of their isolated character and close spatial relationship with the eyes (especially for vein type 1), are also derived from this homogeneous parent. Some possible mechanisms leading to the formation of the veins are discussed below.

We believe that the eyes in the Purnamoota Road gneiss have formed *in situ* by diffusion leading to metamorphic differentiation (cf. Loberg, 1963, p. 76). The eyes simply represent a redistribution of material. It should be noted that most of the eyes are isolated — they have no feeders to them and hence cannot be igneous injected material. Nor do they appear to be relict structures. In addition, the mineralogy and chemistry of the host and the eyes are very similar, with the proportions of light to dark minerals being almost the same (and close to that ratio in the homogeneous phase). Furthermore, we consider that the differentiation took place essentially in the solid state because the minerals show crystalloblastic microstructures.

The similar proportion of light to dark minerals in the eyes and in the matrix indicates that ions probably have diffused essentially within volumes now represented by the eyes themselves. It is evident from the present distribution of minerals in the eyes that the ions Fe and Mg have been preferentially concentrated at the centres whereas elements such as Na and Ca either tended to lag behind movement towards the centre or migrated outwards to the mantle.

The driving force behind this differentiation is not fully understood. Chemical potential gradients promote diffusion of matter and these gradients can be initiated by differences in pressure, temperature, ionic concentration, or even differential stress between domains in a rock system (Vernon, 1976). Accepting that temperature and pressure were essentially the same throughout the gneiss, and noting the similar composition and modal proportion of the minerals, differential stress may well be the main parameter initiating diffusion in these rocks. Further, we suggest that eye formation took place during the metamorphism that produced the matrix and not after it (see, however, Fisher, 1970, p. 95).

The relationship in orientation between an internal biotite clot and its enveloping mantle and the preferred orientation of biotite within the spots (fig. 4) might suggest that the biotite in the eyes was concentrated under the influence of one set of conjugate shear planes in a stress field with σ_1 (the greatest compressive stress, Turner and Weiss, 1963, p. 261) normal to the foliation of the gneiss. Another possibility is that originally spherical biotite spots were subsequently deformed selectively during a later shortening directed almost parallel to the foliation. In their present form, the directed structure of the biotite spots within the Purnamoota Road gneiss contrasts with the isotropic fabric in the segregations described by Loberg (1963).

Diffusion and nucleation of the spots could also be promoted by lowering the grain boundary energy of the system. This may occur by a reduction in the number of grain boundaries between like minerals (although we have not been able to conclusively demonstrate this), by an increase in grainsize of the felsic matrix of the spotted gneiss, and by the development of planar, low angle, rational interfaces (decussate aggregates) in the biotite spots.

The origin of veins in the Purnamoota Road gneiss

Genesis of the veins within the Purnamoota Road gneiss is problematical, as indeed is the origin of many quartzofeldspathic veins in high grade metamorphites. Some workers (e.g. Ashworth, 1976, 1977) hold that similar veins formed by anatexis, whereas others (e.g. Yardley 1977, 1978) suggest that they originated by metamorphic segregation (with igneous injection or external metasomatism as additional possibilities). Related topics in this regard, as applied mainly to migmatites, are summarized and discussed, for example, by White (1966), Mehnert (1968), Olsen (1977) and Yardley (1978), who refer to much of the earlier work.

Two points are important to any appraisal of the origin of veins in the Purnamoota Road gneiss:

(a) the veins appear to be entirely enclosed by their host suggesting an *in situ* formative process such as metamorphic differentiation or partial melting of the enclosing gneiss; and

(b) the volume of the veins, although difficult to estimate, is undoubtedly less than 5% of the total volume of the gneiss — which implies that if the veins originated by anatexis then they must have segregated during the earliest stages of that process. Support for this suggestion is obtained from temperature estimates using biotite and garnet compositions in the spotted gneiss (Table II, columns 1,2,13,14). Calculations based on the procedure outlined in Ferry and Spear (1978) indicate temperatures of 650°C±50°C at pressures between 3 and 4 kilobars and these temperatures are consistent with those found by us for prograde pelitic schists in the same area. Such temperatures indicate that only small amounts of minimum melt could have formed.

Let us initially consider the proposition that the veins within the Purnamoota Road gneiss were derived by partial melting of their host. Data from Table I, in particular the trace element results, are used to test this hypothesis. Equations explaining the theoretical behaviour of trace elements during partial melting have been derived by Shaw (1970) and this topic has been reviewed, for example, by Arth (1976), Allègre and Hart (1978), Allègre and Minster (1978), and Hanson (1978).

We follow the "batch" melting proposition of Arth (1976) because this is the most geologically realistic model for the generation of large, homogeneous bodies of magma where continuous equilibrium exists between residual solid and liquid phases. Clearly, this model does not relate exactly to the small volume of material that must have formed the veins we are considering but it is preferable to models involving either the continuous removal of infinitesimal amounts of liquid from a restite or non-equilibrium partial melting. The grounds for this preference are firstly that the veins in the Purnamoota Road gneiss appear to have formed *in situ* (thus allowing for equilibrium to be continually maintained between melt

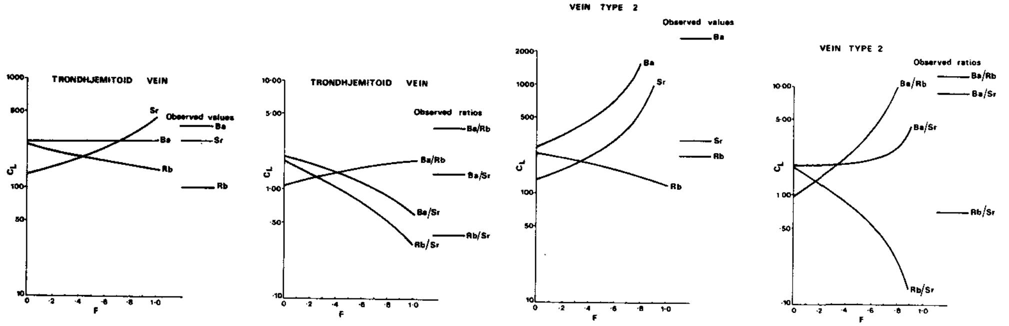

Fig. 5. Plots of calculated Sr, Ba and Rb liquid concentrations (ppm) and Ba/Rb, Ba/Sr and Rb/Sr liquid ratios (both represented by C_L) versus the fraction of melting F. The distribution coefficients are taken from Table II of Hanson (1978). Observed values and ratios are indicated on the right hand side of each diagram.

and restite) and, secondly, that repeated removals of melt are often considered to be physically unlikely (Arth, 1976).

The equation for batch melting (from Hanson, 1978) is given by:

$$C_L/C_0 = 1/\left[D_0 + F(1-P)\right]$$

where:
C_L = weight concentration of trace element in derived melt
C_0 = weight concentration of trace elements in parent
D_0 = bulk distribution coefficient of a given trace element at onset of melting
F = weight fraction of melt relative to parent
P = bulk distribution coefficient of minerals making up melt

and $D_0 = \sum_{i=1}^{n} x^i\, Kd^i$

and $P = \sum_{i=1}^{n} p^i\, Kd^i$

where:
x^i = weight fraction of a given mineral i in parent
Kd^i = mineral/melt distribution coefficient for a given trace element for mineral i
p^i = normative weight fraction of mineral i in melt.

A factor contributing to the uncertainty in C_L/C_0 as a function of F is the magnitude of the Kd's. Values for Kd's are generally determined by studies involving phenocrysts to groundmass trace element abundances in volcanic rocks (e.g. Schnetzler and Philpotts, 1970) and at best can be regarded as approximations when applied to other rock systems. Further, Kd varies as a function of temperature and mineral and melt composition (Hanson, 1978) and such information is not presently available to us.

In all our calculations (the results of which are presented essentially as fig. 5) we have assumed that the Kd's of Ba, Rb and Sr for quartz are close to zero (Hansen, 1978). C_0 is taken to be those analytical values obtained for the parent homogeneous gneiss. The distribution coefficient data are taken from Hanson (1978, Table II). Theoretical trace element modelling for both vein types reveals some similarities in trace element distribution patterns. Theoretical Rb values decrease with, and Sr values increase with, the increase in the fraction of melting. Ba shows an increase with greater F for both veins but this pattern is much more marked for the K-feldspar-rich subtype of vein type 2.

For the trondhjemitoid variety of vein type 1, the observed trace element abundances do not match the theoretical values obtained from the melting model. The Ba value for this vein is greater than, and the Rb value less than, the calculated concentration irrespective of the magnitude of F (fig. 5). The actual Sr concentration of 267 ppm is obtained for approximately 80% partial melting of the host which is clearly unacceptable. The theoretical Ba/Rb ratio does not correspond with the observed value and for the calculated Rb/Sr and Ba/Sr ratios to approach the observed values, F must exceed 40% (fig. 5).

Calculations for the K-feldspar-rich subtype of vein type 2 show that the observed Ba level is in excess of any value determined by the model with Sr matching values for F at 60%. The tabulated Rb value is compatible with the model for low degrees of partial melting. However, observed Ba/Rb and Ba/Sr ratios do not match the calculated ones for F of any magnitude and an F value of 50% is necessary to produce Rb/Sr of 0.71 (fig. 5).

These tentative results lead us to reject the proposition that any of the veins in the Purnamoota Road gneiss were derived by partial melting of their host.

The origin of vein type 1. Structural observations and data on the gross chemistry suggest the following. As noted above, a close relationship exists between vein type 1 and the eyes in space, structure and overall form, and it is reasonable to consider that these veins have developed by a process similar to eye formation involving linking of eyes. Because of this we favour a process involving diffusion as the mechanism which formed vein type 1.

On structural grounds it is difficult to imagine how partial melting could firstly produce biotite spots and secondly maintain them as coherent bodies once they were formed. (It can be argued, in fact, that the partial melting will tend to lead to the removal of biotite to form melts which will crystallize K-feldspar (Yardley, 1978, p. 942)). In addition, the presence of the biotite spots must preclude lateral movement along a vein of any material derived by igneous injection (Yardley, 1978) from outside the gneiss as here again the spots would surely have been dispersed by such a method of transport.

The chemical composition (and mineralogy) of the type 1 veins is different from that which might be expected as a result of anatexis. Because the normative Or is low in the trondhjemitoid subtype, the plot of Q-Ab-Or falls well away from ternary minima and eutectics (Luth et al., 1964). Although the subtype richer in K_2O (Table I, analysis 7) plots nearer the ternary minima and eutectics, it falls in the opposite direction from the higher pressure data presented by Luth et al. (1964). This is contrary to what would be expected under high grade metamorphism. Further, the plagioclase compositions of the veins and the host are virtually identical and this must count against the proposition that the plagioclase of these veins was derived by partial melting of plagioclase of the host gneiss (Misch, 1968; Vernon, 1976, p. 222; Yardley, 1977, 1978).

If metamorphic differentiation is accepted as the formative process for the type 1 veins, it is clear from both chemical and mineralogical data that the veins, unlike the spots, represent localised systems 'open' to the migration of ions. On mineralogical grounds, it appears that the most important aspect of vein type 1 evolution is the partial or complete elimination of K-feldspar with the concomitant production of plagioclase.

The origin of vein type 2. As noted above, an origin by anatexis also seems unlikely for vein type 2. Two further points count against vein type 2 being produced by anatexis. The example of vein type 2 with the high K-feldspar content (Table I, column 9) contains almost 55% normative Or and on a plot of normative Q-Ab-Or it falls well away from ternary minima or eutectics (Luth et al., 1964). Thus it appears difficult to assume that such a rock formed as a result of crystal $\rightleftharpoons$ liquid equilibria. Those varieties of vein type 2 which hold plagioclase (e.g. Table I, column 8) present a further barrier to the anatectic model. The plagioclase (e.g. Table II, column 9) has a composition close to An_{37}, which is virtually the same as the plagioclase in both the homogeneous and spotted phases of the Purnamoota Road gneiss. Such a calcic plagioclase can hardly have been derived from these gneisses by partial melting (Yardley, 1977).

Other modes of origin, such as igneous injection or external metasomatism, may also be feasible. However, these mechanisms divorce vein formation from eye formation and as such destroy the apparent entity of the Purnamoota Road outcrop which may be best regarded overall as a closed system. Some examples of vein type 2 (especially the 'dyke', Table I, column 10 and the vein illustrated in fig. 3E (also Table I, column 9)) appear to disrupt the host gneiss and might have been emplaced by lateral movement involving fluid introductions. On the other hand, fig. 3E shows that varieties of veins 1 and 2 may occur in pairs and, as noted above, these two veins appear locally to merge. Such a close association suggests that both veins have similar origins and we favour metamorphic differentiation as the mode of origin for vein type 2. Furthermore, it is likely that the very K-feldspar-rich veins represent segregation products complementary to the trondhjemitoid veins with biotite spots. The most important aspect of vein type 2 formation is thus the partial or complete elimination of plagioclase (and formation of K-feldspar) by diffusion. We are unsure of the role of biotite in vein type 2 formation, but mineralogical observations suggest to us that this phase is also removed by diffusion.

Lastly, the subtype of vein type 1 with an appreciably high K-feldspar content (Table I, column 7) and the variety of vein type 2 with substantial plagioclase (e.g. Table I, column 8) are chemically similar and intermediate in composition between the trondhjemitoid vein type 1 and the K-feldspar-rich representative of vein type 2. Some of these intermediate rocks may represent the products of incomplete reactions which produced the more strikingly diverse veins.

Conclusion

We have attempted in this paper to present mainly a description of the spotted gneisses and related veins from Purnamoota Road, Broken Hill and to outline processes leading to their formation. Some features of these rocks deserve special mention and should be considered in a general dissertation on spotted gneisses and veins.

(1) The spots in the Purnamoota Road gneiss are unusual because the mafic clots within the mantles are virtually monomineralic, being composed almost entirely of a dense aggregate of biotite. Other flecks, for example from Västervik, Sweden have biotite as only one of the main minerals in a core surrounded by a mafic-free mantle.

(2) The mineralogical relationship between spots, mantle and matrix seems to be relatively simple, involving essentially only quartz, plagioclase, K-feldspar and biotite with minor amounts of muscovite and ilmenite. The composition of these phases is remarkably similar, no matter in what setting they occur.

(3) Although almandine porphyroblasts are developed throughout all domains of the spotted gneiss and in vein type 1, it is not the retrogression of the garnet that has formed the biotite spots.

(4) Irrespective of their origin, the obvious structural relationship between the whole eyes and the central biotite clots and their arrangement in the foliation stands in contrast to the isotropic fabric of the flecks described by Loberg (1963).

(5) The linking of the eyes to form vein-like patches with multiple biotite pupils appears to be an initial process in the development of the veins with spots. It is also notable that the biotite forms clots contained within the veins rather than developing as mafic selvages on the vein margins.

(6) The production of complementary veins of trondhjemitoid and K-feldspar-rich aspect is apparently unusual. Both can be most readily explained by metamorphic segregation.

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