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THE MIGMATIZATION OF HADRYNIAN SEDIMENTARY ROCKS, MICA CREEK, BRITISH COLUMBIA

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ABSTRACT

On the northeast margin of the Monashee–Selkirk metamorphic complex, Mica Creek area, British Columbia, the metamorphic grade rises from lower to uppermost amphibolite facies in rocks of the Windermere Supergroup. Important isograds in pelitic rocks are the appearance of staurolite + kyanite, the disappearance of staurolite, the appearance of sillimanite, the appearance of sillimanite + K-feldspar, and the disappearance of muscovite. Migmatites first occur almost simultaneously with the disappearance of staurolite and become very abundant at the appearance of the sillimanite + K-feldspar isograd. Lower-grade migmatites were produced by anatexis in arkosic rocks, involving the melting of K-feldspar + muscovite + albite + quartz + water. At higher grades the incongruent melting of muscovite + albite + quartz in water-bearing rocks produced aluminosilicate + melt. In both these reactions the extent of melting was limited by the amount of water available. At the isograd marked by the appearance of sillimanite + K-feldspar, vapor-absent melting of quartz + albite + muscovite produced sillimanite + K-feldspar + melt.

Keywords: migmatite, anatexis, Mica Creek, British Columbia, Windermere Supergroup, metamorphic reactions.

SOMMAIRE

A la lisière nord-est du socle métamorphique de Monashee–Selkirk, dans la région du ruisseau Mica (Colombie-Britannique), on note la présence d'un gradient dans le degré de métamorphisme du facies amphibolite, d'inférieur à supérieur maximum dans les roches du supergroupe de Windermere. Voici les isogrades importants dans les roches pélitiques: coexistence de staurotide + disthène, élimination de staurotide, formation de sillimanite, coexistence de sillimanite + feldspath potassique, et disparition de la muscovite. L'apparition des migmatites coïncide sensiblement avec l'élimination de la staurotide; ces migmatites deviennent très abondantes à l'isograde sillimanite + feldspath potassique. Les roches arkosiques ont produit des migmatites à un degré de métamorphisme inférieur, résultat de l'anatexie de l'assemblage feldspath potassique + muscovite + albite + quartz + eau. Où le métamorphisme était plus intense, la fusion incongruente de l'assemblage muscovite + albite + quartz + eau a produit aluminosilicate + liquide silicaté. Dans les deux cas, le degré de fusion était fixé par la disponibilité de l'eau. A l'isograde que marque la coexistence de sillimanite + feldspath potassique, la fusion de quartz + albite + muscovite en l'absence de phase gazeuse a produit sillimanite + feldspath potassique + liquide silicaté.

(Traduit par la Rédaction)

Mots-clés: migmatite, anatexie, Mica Creek, Colombie-Britannique, supergroupe de Windermere, réactions métamorphiques.

INTRODUCTION

The Monashee–Selkirk metamorphic complex, in the Scrip Range of southeastern British Columbia, provides a situation where the miogeoclinal sedimentary rocks of the Horsethief Creek Group (Windermere Supergroup) can be traced along strike from sub-biotite to sillimanite–K-feldspar metamorphic grade, with stratigraphic units repeated several times by large-scale folding (Raeside & Simony 1983). Much of the margin of the Monashee–Selkirk complex is bounded by faults or intrusive rocks, *e.g.*, the Columbia River fault zone, described by Read & Brown (1981), but in the northeast, metamorphic grade increases gradually. The lower-grade metamorphic isograds that have been mapped in the Selkirk Mountains by De Vries (1971) and in the Rocky Mountains by Craw (1978) range from the chlorite zone to the staurolite–Al_2SiO_5 zone. In the northern Selkirk Mountains and the Monashee Mountains, metamorphic grade increases up to the sillimanite + K-feldspar zone (Ghent *et al.* 1982, Leatherbarrow & Brown 1978, Simony *et al.* 1980).

Closely related with the disappearance of staurolite is the first appearance of abundant migmatite. It is pervasive in many pelitic lithologies, and its first appearance can be mapped as an isograd (Fig. 1). It is a composite rock-type made of finely segregated quartzofeldspathic and mafic patches (Fig. 2). Layering may or may not be prominent. The compositions of minerals in the leucosome, melanosome (where present) and paleosome are similar.

A detailed study of the mineral chemistry, petrography and petrology of the migmatites in various quartzofeldspathic rock-types was undertaken with the aim of classifying them, defining the conditions of their development and determining what genetic relationships, if any, they bear to each other.

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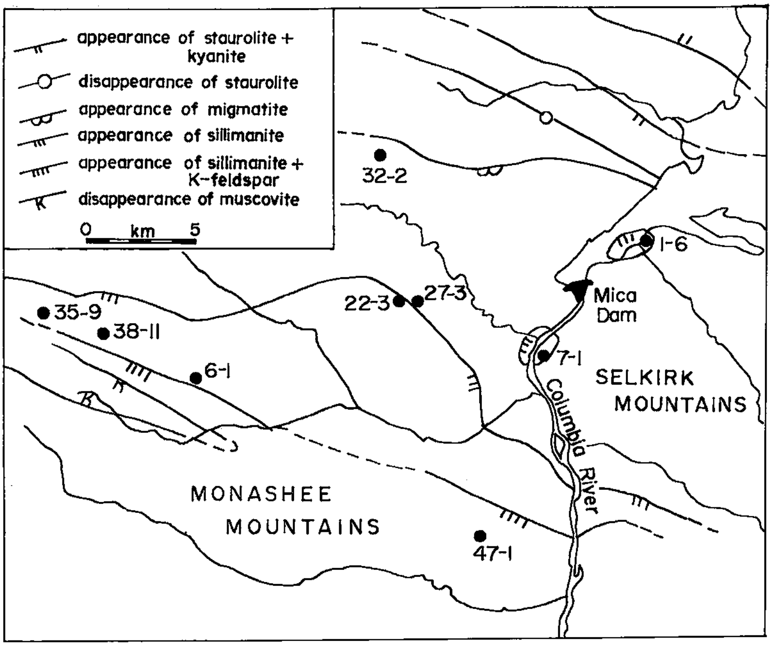

FIG. 1. Map of the Mica Creek area showing metamorphic isograds, the line of first appearance of migmatite and sample localities referred to in the text.

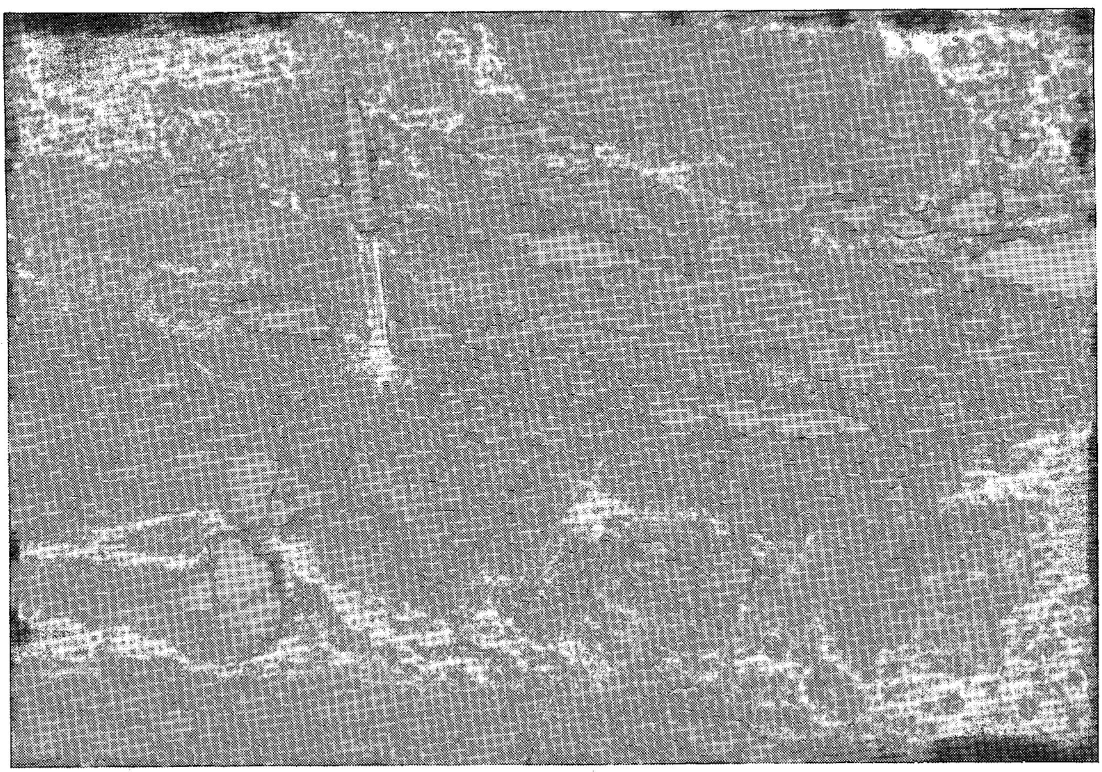

FIG. 2. Outcrop of migmatite in pelite. Neosomes are concordant, leucosomes are lensoid, and connected by thicker melanosomes.

The Occurrence and Formation of Migmatites

Migmatites are typical of high-grade metapelitic rocks. There has been no general agreement on their origin, with various models relevant to different occurrences. These models can be grouped into four categories (after White 1966, Misch 1968, Yardley 1978, Ashworth 1985): (1) layered injection of felsic magma along foliation planes, (2) anatexis with local segregation of the melted material, (3) metasomatism with the introduction of K or Na from an external source, and (4) subsolidus metamorphic differentiation, either by mechanical or chemical processes.

Criteria that can be used to determine the process of migmatization are (also see Ashworth 1985): (1) a comparison of the bulk composition and field relationships of the migmatized rocks with their unmigmatized equivalents (*e.g.*, Engel & Engel 1958, Brown 1967, Pitcher & Berger 1972, Olsen 1977, 1982); (2) a comparison of the leucosome composition with that of the initial melts in synthetic systems (*e.g.*, Brown 1967, Misch 1968, Dougan 1979); (3) textural criteria, such as orientation of relict minerals (Goodspeed 1948), leucosome morphology (Yardley 1978) or replacement textures (*e.g.*, King 1965, Misch 1968, Ashworth 1976), and (4) mineralogical criteria, such as plagioclase compositions (Misch 1968, Olsen 1977, Yardley 1978) or assemblages of metamorphic minerals (Kretz 1966, Tracy 1978).

In spite of the large numbers of studies of migmatization, these criteria have failed, in all but a few cases, to demonstrate conclusively the mechanism of migmatization. Three main factors are responsible for this failure: (1) only rarely can stratigraphy be traced from migmatized areas to unmigmatized equivalents; (2) textural and compositional evidence has been obscured by later recrystallization or alteration; and (3) commonly more than one mechanism of migmatization was operating.

Migmatites of the Scrip Range

Migmatites of the Scrip Range provide an opportunity for study where there is a good control on stratigraphy and structure, where the temperature, pressure and water fugacity of metamorphism have been independently estimated and where little post-migmatization alteration or recrystallization has occurred. The migmatites are developed in pelitic and semipelitic lithologies of the Horsethief Creek Group, a 6000-m-thick sequence of clastic metasedimentary rocks with less abundant mafic, calc-silicate and psammitic layers. Unmigmatized equivalent rocks exist nearby at lower metamorphic grades. Migmatization has chiefly affected the most pelitic lithologies, but in many places it is more extensively developed in arkosic semipelites, whereas nearby pelites remain unmigmatized. Some amphibolites also contain leucocratic and melanocratic layers. A particularly common rock-type is a muscovite–biotite pelite, lacking in K-feldspar. The lowest-grade occurrence of abundant migmatites in such pelites can be mapped as a line that lies close to the isograd that marks the disappearance of staurolite, although in the western part of the study area, the first appearance of migmatite deviates into the kyanite zone (Fig. 1). The position of the line marking the appearance of migmatite in these pelites indicates that its appearance in pelites is, to a first approximation, controlled primarily by metamorphic grade. Arkosic K-feldspar-bearing semipelites also occur sporadically in the sequence. Migmatite is developed in these at a lower metamorphic grade than in the pelites and occurs as continuous segregated bands parallel to bedding. These arkosic rock-types account for less than 5% of the outcrop area and appear to be migmatized throughout the map area shown in Figure 1.

From the first occurrence of pelitic migmatite in the kyanite zone to the beginning of the muscovite + quartz decomposition in the sillimanite zone, the amount of neosome is restricted to about 30% in pelites. In this zone of limited migmatization, outcrops of pelite are most commonly veined by elongate pod-like segregations of quartz and feldspar that are normally concordant to the foliation (Fig. 2). The maximum development of migmatite is observed in very aluminous rocks, which typically possess a strong foliation and crenulation cleavage; there, the leucosome patches are often disrupted and broken by the crenulation cleavage. According to the classification scheme of Mehnert (1971), the predominant migmatite structure is stromatic (layered), with folded and ophthalmitic (augen) varieties. Pods of leucosome are commonly, but not universally, bounded by melanosomes, and have dimensions of up to 5 cm thick and up to 1 m parallel to the foliation. Commonly, however, pods are less than 3 × 30 cm in size. The development of a melanosome is erratic; some migmatites have a clearly developed melanosome of biotite, garnet and aluminosilicate up to a thickness equal to that of the leucosome; some have discontinuous biotite concentrations on the margins of, and enclosed by, leucosomes; others have no distinguishable melanosome. In layers of pelite that are more than 5 cm thick, paleosome is typically preserved. The paleosome is a medium-grained lepidoblastic to granoblastic rock, typically composed of the same phases as are present in the leucosome. In thin pelitic layers (less than 5 cm), the entire layer is represented by neosome. with discontinuous coarse-grained leucosome and an enclosing continuous melanosome displaying a pinch-and-swell structure.

At higher metamorphic grades than the beginning

TABLE 1. COMPOSITION OF PLAGIOCLASE (An mol %) IN LEUCOSOME AND PALEOSOME OF MIGMATITES

Sample	Leucosome composition	Paleosome composition
1-6	27.9	29.8
6-1	19.3	19.8
7-1	27.2	33.1
22-3	14.9	15.3
32-2	20.8	21.2
35-9	28.3	28.6
38-11	27.3	24.3
47-1	23.0	22.8

of the decomposition of muscovite + quartz, the pelitic and semipelitic rocks are less micaceous and take on a gneissic character. Pelitic rocks show an extensive development of sillimanite–quartz nodules, and migmatites are relatively poorly developed. At this grade, between 30% and 50% of the outcrops consists of intrusive and pegmatitic rocks of trondhjemitic to granodioritic composition. The bodies range in size from small accumulations not significantly larger than migmatitic leucosomes to bodies over one square kilometre in outcrop area. It is commonly impossible to distinguish the smaller intrusive bodies from migmatitic leucosomes. Pelitic rocks are recognized by the presence of large amounts of sillimanite and biotite, which probably represent melanosome from which leucosome material has been extracted and removed. The few paleosomes that are preserved occur as wispy bodies. Semipelitic rocks also display evidence of migmatization at higher metamorphic grades. They occur as regularly layered banded gneisses, with layers 1–5 cm thick and continuous across outcrops. Because semipelites are impoverished in micaceous minerals, they have a gneissic, rather than a schistose fabric.

Mineralogy and Petrology of the Scrip Range Migmatites

Migmatites from pelitic lithologies were sampled from just above the isograd marking the appearance of staurolite + kyanite to above the isograd marking the appearance of sillimanite + K-feldspar. Thin sections were made of 28 samples; most of these were also stained to determine the abundance of K-feldspar and plagioclase, and electron-microprobe analyses were made of all major phases in eight samples. Although the migmatites display a considerable range of compositional variation, mineral compositions within a single hand-specimen are similar in leucosome, melanosome and paleosome. Usually only quartz and feldspar are present in all three, but

TABLE 2. MODAL ABUNDANCES OF LEUCOSOME, MELANOSOME AND PALEOSOME PHASES IN MIGMATITES, MICA CREEK, B.C.

	TYPE 1 MIGMATITES														
	1-6				6-1			7-1				22-3			
	leuc	mel	pal	sum	leuc	mel	pal	leuc	mel	pal	sum	leuc	mel	pal	sum
n	1500	680	1475		988	665	1155	1248	755	2000		1008	685	1120	
e	2.6	3.8	2.6		3.2	3.9	2.9	2.8	3.6	2.2		3.1	3.8	3.0	
quartz	6.0	13.5	9.3	9.2	43.5	54.6	68.7	40.5	22.5	33.3	33.8	24.9	12.4	16.5	16.1
plagioclase	85.8	34.2	61.8	62.2	38.2	12.5	68.7	53.2	21.2	40.2	41.2	60.5	7.0	23.3	23.0
kyanite	–	5.0	2.5	2.2	–	–	–	–	4.6	1.5	1.7	–	–	–	–
andalusite	1.6	–	–	–	.9	–	–	–	–	–	–	–	–	–	–
sillimanite	–	tr	.1	nc	15.2	tr	tr	–	–	–	–	–	12.0	tr	8.4
biotite	–	35.1	16.2	15.4	tr	17.8	10.1	.8	18.1	12.0	11.0	2.7	51.6	36.8	36.9
garnet	–	3.1	1.2	1.4	–	7.5	1.2	–	14.0	5.8	5.2	2.5	12.2	9.2	9.3
chlorite	1.5	5.1	4.5	3.1	–	–	–	–	–	–	–	–	–	–	–
muscovite	5.1	3.0	4.2	4.1	2.3	6.2	4.3	5.5	9.6	7.4	7.0	3.6	3.2	9.4	3.3
opaques	–	2.0	.2	.9	.5	.6	tr	–	tr	.3	nc	–	1.2	.5	nc
sum composed of:	.56 + .44							.625 + .375				.32 + .68			

	TYPE 1 MIGMATITE				TYPE 2 MIGMATITES						TYPE 3 MIGMATITE		
	32-2				35-9			38-11			47-1		
	leuc	mel	pal	sum	leuc	mel	pal	leuc	mel	pal	leuc	mel	pal
n	1078	511	670		950	480	1162	570	393	842	422	414	1211
e	3.0	4.4	3.9		3.2	4.6	2.9	4.2	5.0	3.4	4.9	4.9	2.9
quartz	49.5	47.3	48.8	48.0	55.2	tr	33.8	42.0	22.6	63.6	28.6	8.3	38.0
plagioclase	40.7	21.3	32.4	33.0	28.8	31.1	31.6	31.2	6.4	23.1	40.6	22.1	28.5
K-feldspar	8.5	3.8	6.5	6.8	16.0	–	–	18.8	1.5	–	27.1	28.5	24.3
sillimanite	–	–	–	–	–	35.2	11.0	2.5	25.8	5.5	tr	14.9	.7
biotite	–	9.7	4.2	4.3	–	8.8	3.1	5.5	8.7	2.6	–	12.4	4.3
garnet	–	–	–	–	–	24.9	10.2	–	2.2	1.5	1.7	4.0	2.4
chlorite	–	–	–	–	–	–	.3	–	–	–	–	1.6	.2
muscovite	1.3	16.5	7.3	7.8	–	–	10.1	–	32.7	3.7	2.0	8.2	1.1
opaques	tr	.3	.2	nc	–	.5	.3	tr	tr	tr	–	tr	tr
sum composed of:	.58 + .42												

Abbreviations: n = number of counts; e = coefficient of variation, expressed as a percentage; leuc, mel and pal represent leucosome, melanosome and paleosome, respectively.

the plagioclase compositions are similar. A slight enrichment in albite is observed in some leucosomes, but the largest variation between leucosome and paleosome is 4 mol % An (Table 1). Garnet grains in neosome and paleosome also show a similar pattern of zoning.

Eight samples that exhibit a wide variety of textures, mineral assemblages and extent of migmatization were selected for detailed analysis. In considering the mechanism of migmatization, particularly relevant features include the metamorphic grade, the presence of muscovite, aluminosilicate and K-feldspar, and whether a sample can be demonstrated to be a closed system. Because field relationships indicate that there is a tendency for the leucosome component of the neosome to be irregularly layered, forming pods or lenses rather than layers, thin-section-scale observation of migmatites may be misleading with respect to absolute amounts of mineral phases. Using mineral assemblages and metamorphic grade, the migmatites can be classified into three types: 1) K-feldspar or aluminosilicate absent in neosome and paleosome, 2) K-feldspar present in neosome, aluminosilicate + muscovite present in paleosome, and 3) K-feldspar + sillimanite present in neosome and paleosome.

Closed systems appear probable for some samples, on the scale of a thin section. In types 1 and 3, the modes of neosome and paleosome are approximately equal; in type 2, the modes, if recalculated in terms of oxides, are similar. In each type, however, examples can be found in which closed-system conditions cannot be demonstrated, either because leucosome has migrated or melanosome is absent. These types are summarized on Table 2, which also presents the modal compositions.

The migmatites of type 1 equilibrated at metamorphic conditions of lower grade than the isograd marking the appearance of K-feldspar + sillimanite. With the exception of the andalusite-bearing sample (1–6), the same phases are present in the neosome and paleosome. Samples 1–6, 7–1 and 22–3 contain kyanite, 6–1 and 22–3 contain sillimanite, and 32–2 contains K-feldspar, but lacks aluminosilicate. Some of these have demonstrably closed-system compositions (for example 1–6, 7–1, 22–3 and 32–2; Table 2), which indicates that the leucosome and melanosome formed from the paleosome by simple segregation, without the addition or removal of material except volatiles. These neosomes must therefore have formed by metamorphic differentiation or anatexis, and not by injection of igneous material or large-scale metasomatism. Textural and compositional criteria have been used by various authors to distinguish the mechanism of migmatization (*e.g.*, Yardley 1978). Of those criteria recognized for anatectic migmatization, most are displayed by the Scrip Range migmatites; 1) bulk-rock composition remains unchanged, 2) mineral assemblages in the neosome differ from those of the paleosome by the addition

TABLE 3. COMPUTED COMPOSITIONS OF LEUCOSOME, MELANOSOME AND PALEOSOME PHASES IN MIGMATITES OF MICA CREEK

	TYPE 1 MIGMATITES														
	1–6				6–1			7–1				22–3			
	leuc	mel	pal	sum	leuc	mel	pal	leuc	mel	pal	sum	leuc	mel	pal	sum
SiO_2	61.8	53.5	58.0	58.1	74.1	74.2	84.4	76.3	58.1	69.1	69.5	69.1	47.4	55.1	54.4
TiO_2	0.1	1.1	0.6	0.5	0.0	1.0	0.1	0.3	0.9	0.4	0.4	0.1	1.4	1.1	1.0
Al_2O_3	24.4	21.4	22.8	23.0	19.1	9.9	7.2	15.7	20.1	17.4	17.4	18.8	22.3	19.6	21.2
FeO	0.3	9.8	4.9	4.5	0.5	7.2	2.7	0.2	10.5	4.8	4.1	1.2	12.4	8.8	8.8
MgO	0.2	3.9	2.0	1.8	0.0	1.6	0.8	0.1	3.0	1.3	1.2	0.5	7.1	5.1	5.0
CaO	5.4	2.2	3.9	4.0	1.6	0.6	0.7	3.7	1.8	2.9	3.0	1.9	0.6	1.0	1.0
K_2O	0.7	3.8	2.2	2.0	0.3	2.6	1.6	0.8	4.0	2.1	2.0	0.7	5.6	4.8	4.1
Na_2O	7.0	2.9	5.1	5.2	3.6	1.2	1.5	4.1	1.8	3.1	3.2	7.6	1.1	3.2	3.2
H_2O	0.3	1.6	1.0	0.9	0.1	1.0	0.6	0.2	1.5	0.8	0.7	0.2	2.3	1.9	1.6
sum composed of:	.56 + .44							.625 + .375				.32 + .68			

	TYPE 1 MIGMATITE				TYPE 2 MIGMATITES							TYPE 3 MIGMATITE		
	32–2				35–9				38–11			47–1		
	leuc	mel	pal	sum	leuc	mel	pal	sum	leuc	mel	pal	leuc	mel	pal
SiO_2	81.0	74.5	78.2	78.3	83.0	44.4	66.7	66.9	77.3	56.4	83.8	70.6	54.9	73.0
TiO_2	0.0	0.4	0.2	0.2	0.0	0.2	0.1	0.1	0.2	0.5	0.1	0.2	0.4	0.6
Al_2O_3	11.7	13.9	12.4	12.6	10.2	37.0	21.6	21.4	13.3	30.7	10.6	18.0	27.6	15.3
FeO	0.1	1.7	0.6	0.7	0.0	9.4	4.0	3.9	1.2	3.2	1.2	0.4	4.8	1.2
MgO	0.0	1.0	0.4	0.4	0.0	2.2	1.0	0.9	0.4	1.1	0.3	0.0	1.0	0.5
CaO	1.9	1.0	1.5	1.5	1.7	2.2	2.0	1.9	0.6	0.2	0.5	3.8	2.4	2.5
K_2O	1.5	3.2	2.2	2.2	2.4	0.9	1.6	1.8	3.0	4.8	0.7	4.3	6.4	4.2
Na_2O	3.7	2.1	3.0	3.0	2.6	2.6	2.6	2.6	3.5	0.8	2.4	2.9	1.8	2.1
H_2O	0.1	0.9	0.4	0.4	0.0	0.5	0.5	0.2	0.2	1.5	0.2	0.1	0.8	0.2
sum composed of:	.58 + .42				.583 + .417									

Abbreviations: leuc, mel and pal represent leucosome, melanosome and paleosome, respectively.

of K-feldspar, 3) planar neosomes are rare, 4) leucosomes are rarely pegmatitic, and 5) neosomes are most extensively developed in those layers with lowest melting temperatures. The only criterion that is not well displayed by the migmatites of the Scrip Range is an albite enrichment in leucosome plagioclase with respect to paleosome plagioclase [see also Ashworth (1985)].

A possible reaction involving a melt phase was described by Thompson & Algor (1977) and Thompson & Tracy (1979):

$$\text{muscovite} + \text{K-feldspar} + \text{albite} + \text{quartz} + H_2O = \text{melt} \quad (1)$$

Because melting is restricted by the amount of the least-available reactant, the total amount of melt produced by this mechanism is necessarily limited.

Migmatites of type 2 contain K-feldspar in the neosome and sillimanite + muscovite in the paleosome, and occur abundantly in the sillimanite + K-feldspar zone of metamorphism. Two samples from this zone are included in Table 2, and both are characterized by relatively coarse-grained leucosomes composed predominantly of quartz, plagioclase and K-feldspar. Plagioclase in sample 35–9 has a similar An content in leucosome, melanosome and paleosome; in sample 38–11, the plagioclase is enriched by 3 mol % An in the leucosome. Both samples display melanosomes strongly enriched in fibrolite. Because of the presence of K-feldspar in the leucosomes, it is not possible to compare the modes of neosome and paleosome to determine if the sample has behaved as a closed system. Instead, the modes have been recalculated to chemical compositions (Table 3). In doing so, minerals were considered homogeneous. This is not the case in garnet, but because its proportion is normally small, and similarly zoned garnet is present in both melanosome and paleosome, the effect is considered negligible. The error involved by ignoring mineral zoning is probably less than that in estimating the mode, and it is not significant when compositions produced by such recalculations are compared. Sample 35–9 appears to have remained a

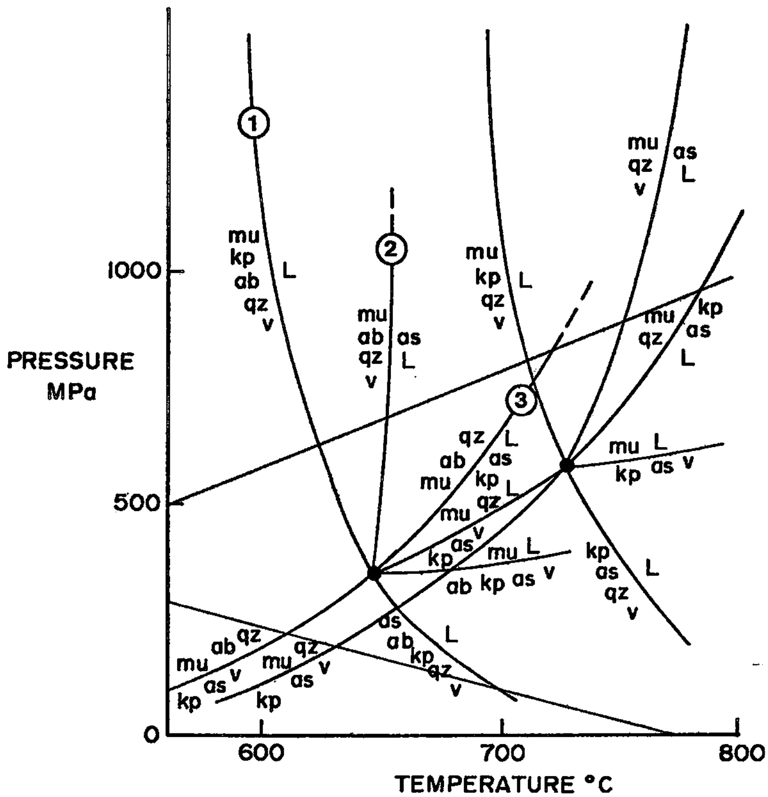

FIG. 3. Reaction equilibria in the system KNASH, after Thompson & Algor (1977, Fig. 8). Reactions 1, 2 and 3 are relevant to the Scrip Range migmatites and are described in the text.

closed system with respect to the major oxides, but 38–11 cannot be simply interpreted, probably because of very narrow neosomes, which made accurate modes difficult to obtain.

The closed-system condition demonstrated by sample 35–9 again indicates that either metamorphic differentiation or anatexis was the mechanism of migmatization; the restriction of K-feldspar to the leucosome indicates that a K-feldspar- or melt-forming reaction was also involved. It is possible that the leucosome represents a melt phase involving the reaction described by Thompson & Algor (1977):

$$\text{muscovite} + \text{albite} + \text{quartz} + H_2O = Al_2SiO_5 + \text{melt} \quad (2)$$

Large amounts of fibrolite are found in the melanosome, on the margin of the leucosome, indicating that this reaction has occurred. In the kyanite zone, large blades of kyanite occur in leucosomes with granodioritic composition.

Type-3 migmatites occur only in zones bearing K-feldspar + sillimanite. Neosomes are similar to those in type-2 migmatites, but the assemblage sillimanite + K-feldspar + quartz + muscovite occurs in the paleosome also. Textural, modal and compositional analogies to type-2 migmatites indicate that the leucosomes of type 3 might also be the result of anatexis, and the K-feldspar + sillimanite assemblage indicates that metamorphic conditions are sufficient to allow vapor-absent melting to begin according to the reaction (Thompson & Algor 1977):

$$\text{muscovite} + \text{albite} + \text{quartz} = \text{K-feldspar} + \text{sillimanite} + \text{melt} \quad (3)$$

Because the amount of melt produced is no longer dependent on the amount of water, the reaction may be considered to have proceeded until one of the mineral phases was consumed. This reaction is responsible for the appearance of the sillimanite + K-feldspar isograd and marks the beginning of the zone of extensive migmatization. In this zone, pelites are relatively rare and universally migmatized, semipelites display common migmatization phenomena, and sillimanite-quartz nodules become very abundant.

TABLE 4. ESTIMATES OF $f(H_2O)$ AND $X(H_2O)$ IN MIGMATITES, SEMIPELITES, PELITES AND A FOLIATED BODY OF INTRUSIVE TRONDHJEMITE

Sample number	Rock type	Al_2SiO_5 polymorph	ln K_D	log K_S	T	P	mica a_{pa}	plag a_{ab}	fH_2O	XH_2O
1-6	migmatized pelite	ky	-1.39	-2.58	720	610	0.33	0.71	543	1.00
		sill				560	0.33	0.71	423	0.80
6-1	migmatized semipelite	sill	-1.45	-2.18	690	650	0.49	0.65	490	0.93
7-1	migmatized pelite	ky	-1.54	-2.14	650	650	0.66	0.77	374	0.88
22-3	migmatized semipelite	ky	-1.71	-1.53	590	610	0.63	0.86	305	0.76
		sill				640	0.63	0.86	342	0.77
4-9	semipelite	ky	-1.51	-2.02	665	670	0.29	0.65	340	0.60
		sill				660	0.29	0.65	322	0.58
11-3	pelite	ky	-1.81	-1.33	555	650	0.76	0.58	284	0.70
13-1	pelite	ky	-1.81	-1.47	555	620	0.81	0.73	232	0.62
27-3	trondhjemite	sill	-1.40	-2.31	760	710	0.25	0.81	485	0.64

Temperatures calculated after Ferry and Spear (1978), pressures after Ghent (1976). $\ln K_D = (X^{gt}_{Fe} \cdot X^{bi}_{Mg} / X^{gt}_{Mg} \cdot X^{bi}_{Fe})^3$; $\log K_S = 3\log X^{gt}_{gr} - 3\log X^{plag}_{an}$;

ab = albite, an = anorthite, bi = biotite, gr = grossular, gt = garnet, ky = kyanite, pa = paragonite, plag = plagioclase, sill = sillimanite, T in degrees C, P in megapascals. Where two pressures are indicated, the values have been calculated using the aluminosilicate polymorph in the third column.

Discussion

Three possible reactions involving the production of melt have been recognized in the migmatites from the Scrip Range. For an isobaric metamorphic path in the order of 700 MPa (Fig. 3), the first melt would be produced at 620°C (or up to 60°C higher, depending on the anorthite content of the plagioclase; Johannes 1985) in muscovite + K-feldspar + plagioclase + quartz assemblages if water were provided by other dehydration reactions, for example, the decomposition of staurolite. Values of water fugacity are calculated using the equilibrium paragonite + quartz = albite + kyanite (or sillimanite) + H_2O (Ghent 1975), and the temperatures and pressures derived from garnet - biotite geothermometry and garnet - plagioclase - aluminosilicate - quartz geobarometry (Table 4). Some of the temperatures estimated for migmatites (Table 4) and temperatures estimated for metamorphic rocks near the kyanite–sillimanite isograd (Ghent *et al.* 1982) are below the beginning-of-melting temperatures for quartz - plagioclase - muscovite - K-feldspar assemblages for $P(H_2O) = P_{total}$ (Fig. 3). If the migmatites actually formed by partial melting, this disagreement could be due to: (a) metamorphic temperatures that are not peak metamorphic temperatures due to Fe–Mg exchange between garnet and biotite during cooling; (b) inaccuracies in the P–T–$a(H_2O)$ calibration of either or both the garnet–biotite geothermometry and the beginning of melting experiments, and (c) the presence of additional components, *e.g.*, boron (Johannes 1985), which could significantly reduce the beginning of melting temperatures. Assuming that other fluid components act only as dilutants and that there is ideal mixing in the fluid phase, the activity of water $a(H_2O)$ can be calculated, where $a(H_2O)$ is the quotient of the fugacity of H_2O calculated for the equilibrium and the fugacity of pure H_2O at the same temperature and pressure. Mole fractions of H_2O are lower in pelites and semipelites that do not display migmatization, ranging from 0.58 to 0.77 in eight samples (Table 4; also, Raeside 1982). These values are comparable to those calculated for staurolite-bearing rocks north of the map area (Ghent *et al.* 1979). In migmatized rocks, the mole fraction of H_2O ranges from 0.88 to 1.00.

Reaction 2 also allows for melting, producing aluminosilicate + melt from muscovite + plagioclase + quartz + water assemblages at about 645°C (Fig. 3). In sillimanite-zone assemblages, a characteristic feature of the products of this reaction is sillimanite-rich melanosome, with up to 40% fibrolite. In kyanite-zone assemblages, kyanite appears as large bladed crystals up to 25 cm long that extend in the leucosomes. Vapor-absent melting can begin with reaction 3, where no free H_2O-rich fluid exists, at about 710°C (Fig. 3). This melting reaction accompanies the sillimanite + K-feldspar isograd reaction, and accounts for the approximate coincidence of the beginning of the zone of extensive migmatization and that reaction. Thompson & Tracy (1979) indicated that melting by reactions 1 and 2 is usually minor in extent. In the Scrip Range, however, suitable lithologies display between 10 and 30% neosome at the first appearance of migmatite. The total volume of neosome does not increase significantly until the appearance of the sillimanite + K-feldspar isograd is crossed. Some suitable silicate assemblages remain unmigmatized (*e.g.*, the paleosomes of migmatites), and it is possible that the controlling factor was subtle differences in differential stress or the activity of water, or some other species, *e.g.*, boron or HF. There is no observable textural or mineralogical evidence to suggest other reasons for lack of migmatization. Neither are migmatites preferentially developed around the intrusive bodies. Some intrusive rocks have a foliation parallel to the regional foliation, indicating that they predate the main metamorphism and deformation. These bodies may contain the assemblage garnet + sillimanite + biotite + muscovite + quartz + plagioclase, suitable for the estimation of P–T–X_{fluid} conditions (*e.g.*, Table 4, sample 27–3). Although the zonation of garnet and plagioclase makes the estimates less precise, it appears that the trondhjemites were not a source of water during intrusion or metamorphism. The coincidence of the first appearance of migmatites with the disappearance-of-staurolite isograd suggests that staurolite decomposition was the dehydration reaction that liberated water and permitted the initial migmatization.

Type-1 and type-2 migmatites are both derived by melting reactions. The restriction of K-feldspar to the leucosomes in type-2 migmatites can be understood by considering the aluminum content of the melt. Reaction 1 results in the direct production of an aluminous melt, whereas reaction 2 is an incongruent melting reaction producing aluminosilicate and a less aluminous melt. K-feldspar may crystallize from the less aluminous melt, whereas muscovite forms from the more aluminous melt produced by reaction 1.

Thompson (1982) noted that dehydration melting of rocks in the system $NaAlO_2$–$KAlO_2$–FeO–MgO–Al_2O_3–SiO_2–H_2O would begin 5 to 10°C below reaction (1) with the reaction:

$$\text{Fe-muscovite} + \text{albite} + \text{Fe-biotite} + \text{K-feldspar} + \text{quartz} + H_2O = \text{melt} \quad (4)$$

Petrographic evidence from the rocks in this study does not support this reaction, as no Fe–Mg-bearing minerals are in the leucosome. Biotite and garnet are enriched in the melanosome, indicating that they are either less involved or not at all involved in the reaction. These observations support the hypothesis that as a direct result of the liberation of water by the reaction of staurolite + muscovite + quartz, anatexis was initiated. Thompson (1982) also indicated that melting upon dehydration is most extensive at higher metamorphic pressures. This observation is supported by our observation, in the Monashee–Selkirk metamorphic complex, that migmatization is most prevalent in the higher-pressure sectors of the complex. In lower-pressure areas to the east and west (Pell & Simony 1981, Dechesne *et al.* 1984, Doucet *et al.* 1985), large volumes of migmatite are not encountered until the sillimanite zone is reached.

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