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Evidence from feldspar compositions of high temperatures in granite sheets in the Scourian complex, N.W. Scotland

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ABSTRACT. Mesoperthite feldspars from hypersolvus granites, with granulite-facies mineralogy from the Scourian complex, N.W. Scotland have an average bulk composition of $(Ab_{0.58}Or_{0.42})_{88}An_{12}$. The mesoperthites have an Ab/Or ratio close to the critical composition of the alkali feldspar solvus for anorthite-free compositions. The critical temperature of the ternary feldspar solvus is estimated at high anorthite contents and used to indicate a temperature in excess of 1000 °C for the crystallization of the granite sheets prior to granulite-facies metamorphism and permits a maximum water content in the melt of 1%.

GRANITIC rocks (*sensu stricto*) represent a minor part of the granulite-facies gneisses of the Scourian complex. Samples were collected from the area between Badcall and Scourie, Sutherland, where granites form sheets two and three metres wide and up to a few hundred metres long which intrude tonalitic gneiss and metagabbro. Granites in this area represent the last stages of crystallization of a tonalite-trondhjemite-granite suite (Rollinson and Windley, 1980). They have been subsequently metamorphosed to granulite facies and have the mineralogy bluish quartz + alkali feldspar ± plagioclase feldspar ± iron-titanium oxides + orthopyroxene or almandine garnet.

Feldspars in the granitic rocks show a wide range of textures, compositions and structural states and include the assemblages orthoclase-mesoperthite, orthoclase-mesoperthite + plagioclase and orthoclase-mesoperthite + plagioclase + microcline. It should be noted, however, that not all the feldspar assemblages are in equilibrium.

Mesoperthite textures. Mesoperthite intergrowths in two-feldspar and hypersolvus granites are of two main textural types. There are fine, regularly spaced (4 μm) crystallographically oriented lamellae of orthoclase in plagioclase (fig. 1*a*), which are either continuous over the whole length of the grain or which bifurcate and taper to a point. The lamellae are uniformly developed throughout the grain and there is no significant variation in lamellar width. There are also broad (40 μm) irregular lamellae (fig. 1*b*) with no preferred crystallographic orientation. In fig. 1*c* fine regularly spaced lamellae in the centre of the grain pass abruptly into coarse irregular lamellae at the edge of the grain indicating that the coarse lamellae developed from the fine. The texture in fig. 1*c* suggests that the main control on perthite coarsening was the availability of a fluid phase which was unable to circulate freely.

The results of iron-titanium oxide thermometry and oxygen barometry in the same samples suggest that a hydrous fluid phase was introduced into the Scourian granites in the temperature interval 660 °C to 530 °C during cooling from the granulite-facies metamorphism (Rollinson, 1980). This agrees well with the results of two-feldspar thermometry (Stormer 1975; Whitney and Stormer 1977) on host-lamella pairs in mesoperthite, which indicate that alkali exchange ceased in the temperature interval 500 to 550 °C. Coarsening of mesoperthite lamellae therefore, probably took place in the presence of a hydrous fluid phase during the retrogression and ceased at about 500 °C.

The orientation and regularity of the fine perthitic intergrowths (fig. 1*a*) closely resemble microperthite textures from igneous rocks of undoubted exsolution origin. This suggests that the Scourian mesoperthites formed by exsolution rather than by syn- or post-magmatic replacement.

Temperature estimates. The evidence for high equilibration temperatures comes from the rare mesoperthite-bearing hypersolvus granites on Scourie More. Hypersolvus granites are instructive in the estimation of crystallization temperature because the rock solidus must lie above the critical

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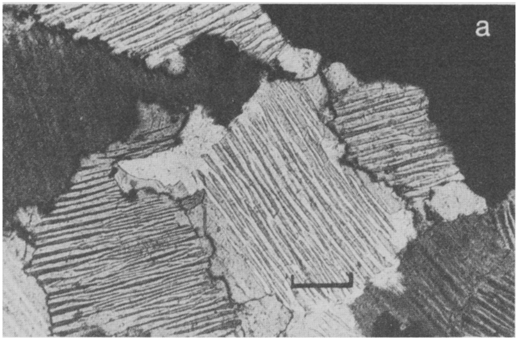

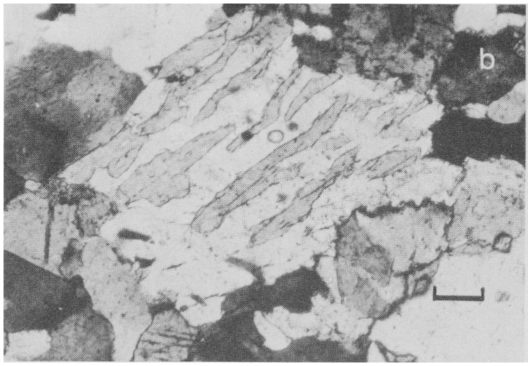

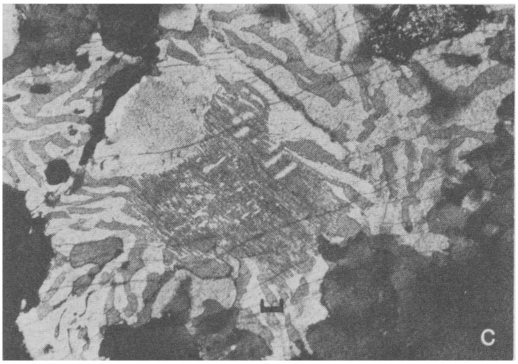

FIG. 1. Photomicrographs of mesoperthite exsolution textures in Scourian granites (crossed nicols). The scale bar is 100 μm. (*a*) mesoperthite in hypersolvus granite, showing fine oriented lamellae of orthoclase in plagioclase; (*b*) mesoperthite showing broad irregular lamellae of orthoclase in plagioclase; (*c*) mesoperthite in two-feldspar granite with fine regularly spaced lamellae in the centre of the grain which pass abruptly into coarser irregular lamellae at the edge of the grain.

temperature of the feldspar solvus. It has been shown (Carmichael, 1963) that the critical temperature of the ternary feldspar solvus increases steeply with increasing anorthite content. This means that the Scourian mesoperthite feldspars, rich in the anorthite component, formed at temperatures substantially higher than the critical temperature in the anorthite-free feldspar system.

The bulk composition of mesoperthite grains in the Scourie More granites was estimated by making scanning analyses with a Cambridge Instruments Microscan V electron microprobe. Operating conditions were 15 kV and a specimen current of 20 na on Cu. A beam 1–2 μm wide and 100 μm long scanned areas of mesoperthite grains normal to the direction of the lamellae for 4 × 10 sec; standards were analysed in the same way. The mean of three scanning analyses for each of six grains is given in Table I and the results plotted in fig. 2.

The mean composition of the Scourian mesoperthites in sample 19 is $(Ab_{0.58}Or_{0.42})_{88}An_{12}$. These feldspars have an Ab/Or ratio close to the critical composition $(Ab_{63}Or_{37})$ in the anorthite-free feldspar system. However, the position of the critical solution curve in the ternary feldspar system is not well known. Assuming that the ternary feldspar solvus has approximately the same shape at An_{12} as the anorthite-free solvus a variation of up to ±20 mol % albite about the critical composition will result in a difference of only about 50 °C in solvus temperature. This means that the Scourian mesoperthites probably crystallized within 50 °C of the critical temperature of the ternary feldspar solvus at An_{12}.

Parsons (1978) estimated that for the constant ratio $Ab_{63}Or_{37}$ the ternary feldspar solvus increases by 32 °C/mol % anorthite. This suggests a ternary solvus temperature of 1040 °C for the composition $(Ab_{0.63}Or_{0.37})_{88}An_{12}$. This is close to the measured composition of the Scourian mesoperthites $(Ab_{0.58}Or_{0.42})_{88}An_{12}$. Given the uncertainties outlined above and the fact that the rock solidus lies above the crest of the ternary feldspar solvus for An_{12} it is likely that the Scourian mesoperthites crystallized at a temperature in excess of 1000 °C.

An estimate of the dry liquidus temperature of the rock can be made from the experimental study of Whitney (1975) on granite R1, which has a similar An content but is slightly more potassic than the Scourian granites. Granite R1 has a dry liquidus temperature of 1170 °C at 0.5 kb and this places an upper limit on the crystallization temperature. There is no firm data for the position of the dry solidus at low pressure for granite R1 but by analogy with the high pressure data in the water saturated system it is likely to be about 80 °C lower

TABLE I. Feldspar Analyses; standard deviation given in parentheses. (Msp - mesoperthite bulk analysis; plag - plagioclase lamella in mesoperthite; or - orthoclase lamella in mesoperthite; n - number of analyses).

Grain	Msp 19/1	Msp 19/2	Msp 19/3	Plag 19/4	Or 19/5	Msp 13/1	Msp 13/2	Msp 13/3	Plag 13/4	Or 13/5
SiO_2	63·78 (.12)	64·48 (.04)	64·31 (.27)	65·74	67·11	64·77 (·23)	64·67 (.58)	64·92 (.23)	64·57	65·23
Al_2O_3	20·87 (.11)	20·73 (.01)	20·86 (.06)	22·83	18·35	20·78 (.12)	20·48 (.17)	20·49 (.37)	22·40	18·46
CaO	2·53 (.06)	2·40 (.10)	2·37 (.10)	4·14	0·00	2·32 (.24)	2·07 (.12)	2·08 (.36)	3·86	0·00
Na_2O	5·84 (.31)	6·01 (.52)	5·77 (·08)	9·13	0·60	5·99 (.40)	5·58 (·37)	6·57 (.66)	9·34	0·73
K_2O	6·64 (·42)	5·77 (.75)	6·86 (.17)	0.14	14·65	6·54 (.74)	7·22 (.64)	6·14 (.94)	0·09	15·71
BaO	0·15 (.01)	0·15 (.01)	0·16 (.03)	0.00	0.39	0·14 (.02)	0·15 (.04)	0.11 (.02)	0.00	0.33
TOT	99·81	99·54	100·33	101·98	101·30	100·54	100·02	100·31	100·26	100·47
An	0·120	0·119	0·113	0·199	0·000	0·110	0·099	0·098	0·185	0·000
Ab	0·502	0·538	0·496	0·793	0·057	0·516	0·485	0·558	0·810	0·066
Or	0·375	0·340	0·388	0·008	0·935	0·371	0·413	0·343	0·005	0·928
n	3	3	3	1	1	3	3	3	1	1

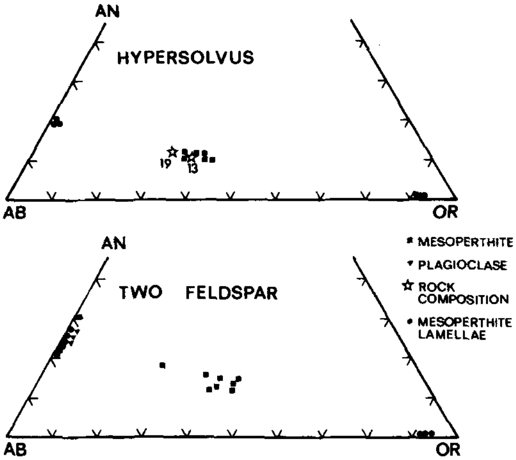

FIG. 2. Feldspar compositions in hypersolvus and two feldspar granites from the Scourie area in the system An–Ab–Or. The normative composition of hypersolvus granites 13 and 19 is also shown.

than the liquidus. This indicates that the solidus for a melt with 1% H_2O will lie close to the crest of the alkali feldspar solvus and restricts the maximum water content of the melt to 1%. At higher pressures the maximum water content is less than 1%.

Discussion. Independent evidence for high temperatures in Scourian granite sheets is given by O'Hara and Yarwood (1978) who applied the two-feldspar thermometer of Stormer (1975) to feldspars from a granite sheet from the north side of Scourie Bay. Some of these feldspars are coarse mesoperthites and have textures similar to those in fig. 1*b* and *c*. O'Hara and Yarwood (op. cit.) obtained a temperature of 1270 °C at 15 kb although this reduces to 1145 °C at 15 kb when the effects of K in plagioclase and Ca in alkali feldspar are included in the mixing equation. If this temperature is recalculated for 0.5 kb pressure it reduces by about 150 °C to *c*.1000 °C and is in good agreement with the results of this study. O'Hara and Yarwood (op. cit.) also report preliminary melting experiments on the same sample; dry melting begins at 1200 °C at 15 kb and is well advanced by 1300 °C. This result can be extrapolated to low pressure using the slope of the dry granite solidus of Huang and Wyllie (1975) and indicates a temperature of *c*.1030 °C at 0.5 kb.

Further evidence of high temperatures in the granitic rocks of the Scourie area comes from the results of Fe-Ti oxide thermometry. Ilmenite-magnetite pairs in the granitic rocks described above yield maximum temperatures of 930 °C but in adjacent cogenetic trondhjemites, temperatures of up to 1035 °C have been recorded (Rollinson, 1979, 1980).

The rocks described above are metamorphosed to granulite facies and O'Hara and Yarwood (1978) have used the results of their two-feldspar thermometry to estimate a temperature of metamorphism of 1150 ± 100 °C. The conditions of the granulite-facies metamorphism of the Scourian complex are well constrained by garnet–pyroxene equilibria and Fe–Ti oxide oxygen barometry to 820 ± 50 °C and 11 kb (Rollinson, 1980, 1981) and are well below the limits proposed by O'Hara and Yarwood (1978).

The results of this study suggest that the high temperatures indicated by mesoperthite compositions in hypersolvus granites of *c*.1000 °C at 0.5 kb relate to the igneous crystallization of these rocks, an event which predated the granulite-facies metamorphism. In the light of this therefore it is probable that the high temperatures recorded by O'Hara and Yarwood (1978) also relate to the igneous crystallization of these rocks rather than to the granulite-facies metamorphism. If this is so, the temperatures of O'Hara and Yarwood should be calculated for lower pressures as it is unlikely that there was a load pressure of 15 kb during the emplacement of the granite sheets; this brings about good agreement between the results of feldspar thermometry and the dry, 0.5 kb solidus temperature of O'Hara and Yarwood (1000 °C and 1030 °C respectively) and the crystallization temperature of mesoperthite feldspars in the hypersolvus granites of this study (*c.*1000 °C).

In summary therefore, temperatures calculated for mesoperthite feldspars from hypersolvus granites in the Scourian complex are *c.*1000 °C and relate to the crystallization of a granitic melt with a maximum water content of 1% H_2O, prior to the granulite-facies metamorphism. These results confirm earlier evidence for high temperatures in the Scourian complex from Fe–Ti oxide thermometry, two-feldspar thermometry and melting experiments (Rollinson, 1979, 1980; O'Hara and Yarwood, 1978).

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