The significance of a Hastingsite granite in the Carn Chuinneag–Inchbae Complex

R. Ian Harker & Timothy Leahy*

Department of Earth and Environmental Science, University of Pennsylvania, Philadelphia, Pennsylvania, 19104–6316, USA

**Present address: IT Corp., Edgewood, MD 21040, USA*

Synopsis

The discovery of a late stage hastingsite gneissic granite in the Inchbae mass (possibly coeval with the riebeckite gneissic granite in the Carn Chuinneag mass) indicates that different physico-chemical conditions prevailed during the last granitic stages of the two masses. This, along with other evidence at the North and SE contacts, is in accord with a previous view that the Inchbae mass is at a different stratigraphic level (lower) relative to the Carn Chuinneag mass.

Introduction

The Carn Chuinneag–Inchbae complex in Easter Ross is a classic example of igneous rocks subjected to regional metamorphism subsequent to their intrusion and consolidation with the formation of a hornfelsed aureole. For a succinct description and map the reader is referred to Johnstone & Mykura (1989).

At the presently exposed surface, the Inchbae mass is separated from the Carn Chuinneag mass to the NE. Both masses consist predominantly of coarse grained granitic augen gneiss (Inchbae Rock). The Carn Chuinneag mass includes amphibolites representing original gabbro and diorite near its NW margin, and a variety of granitic gneisses, including a riebeckite gneissic granite and an albite gneiss with associated cassiterite. The Inchbae mass is apparently less complex, consisting largely of the coarse augen gneiss with a medium grained granitic gneiss along its NE and SW margins. However, in the same vicinity as the hastingsite gneissic granite described below, a green hornblende acid gneiss occurs with abundant quartz, biotite and partially saussuritized plagioclase. In contrast to the hastingsite gneissic granitic it contains much less potash feldspar, more titanite (surrounding opaques), very little garnet and no allanite; apatite is an important accessory. This rock may be part of the small lens of hornblende gneiss marked on the Geological Survey's 1:10560 scale map, sheet LXII, (Peach *et al.* 1912).

Hastingsite gneissic granite

A small outcrop in the Black Water approximately 3.5 km upstream from the Inchbae Lodge reveals a medium grained gneissic granite containing hastingsite (Fig. 1). It shows an intrusive relationship into the surrounding Inchbae rock.

The limits of the hastingsite-bearing rock are inferred from drift on the south side of the river and on the north side of route A835 where the first specimen was found. Gneissic aplite also occurs in the same vicinity in the Black Water.

Thin section examination shows that the essential minerals in the hastingsite gneissic granite are quartz (with shadowy extinction), feldspar (mostly K-feldspar and minor oligoclase), biotite (brown with some flexed crystals), garnet and hastingsite. Accessory minerals include titanite, allanite, as yellow cores in epidote in some places, and opaque minerals. The feldspar forms small augen up to about 1 cm across in addition to occurring in the groundmass. The amount of biotite and the degree of alteration of the hastingsite are somewhat variable.

The hastingsite occurs in anhedral crystals, many poikilitic, up to 2 mm across. In places the crystals are arranged in bands parallel to the foliation. The hastingsite shows a tendency to be altered to greenish brown mica.

Analytical details

Analyses of the hastingsite gneissic granite and of the hastingsite itself were carried out in duplicate by emission spectroscopy in a Spectrospan Model IIIB argon plasma direct current system at Rutgers University by Dr. Michael J. Carr according to the protocol described by Feigenson & Carr (1985). In addition to calibrating the instrument with known rock standards, two samples of the previously analyzed hornblende from the Carn Chuinneag mass (Hornblende I in Harker 1962) were analyzed as reference materials.

Microanalyses of a carbon-coated thin section of the hastingsite granite were carried out by Dr. Jeremy Delaney at Rutgers University using a JEOL JXA 8600 Superprobe. Calibration standards were run for each of the elements to be analyzed. The raw output data was processed by a Bence–Albee program to produce relative

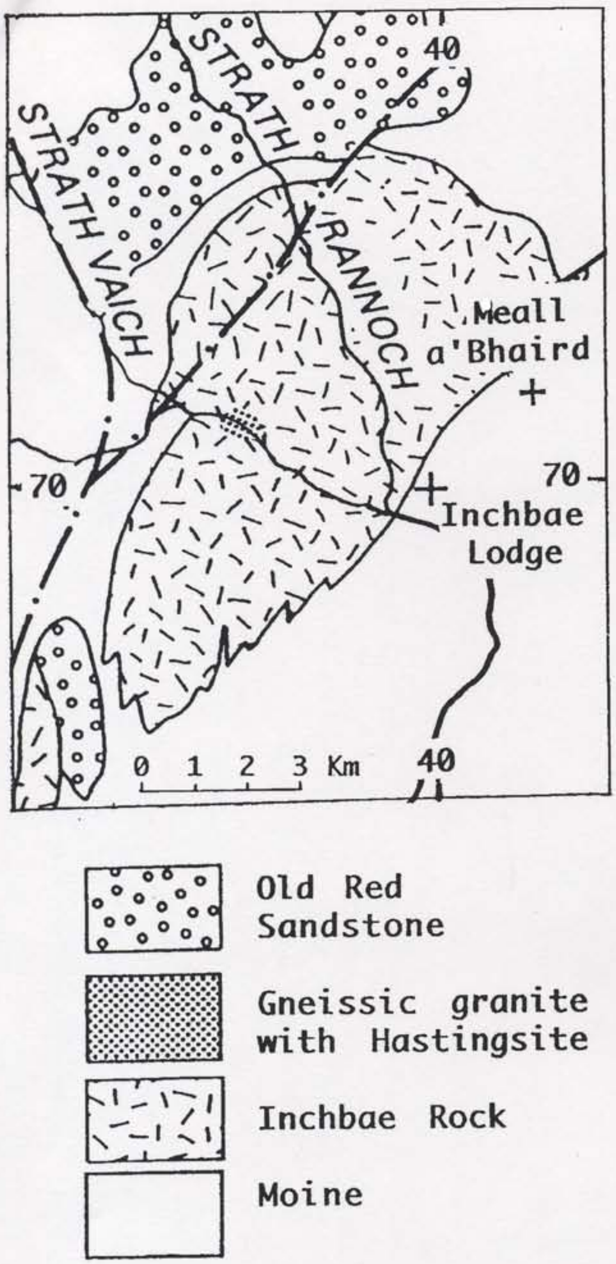

FIG. 1. Map of Inchbae mass, Easter Ross.

abundances adjusted for interference (Bence & Albee 1968, Albee & Ray 1970). The average of 6 electron microprobe analyses of the amphibole differed from the analysis by emission spectroscopy by less than 0.22% for all constituent oxides except CaO (0.66% higher) and MgO (0.36% lower).

The FeO content of the rock was determined by Dr. Gene Ulmer at Temple University. One to two-gram weighed samples of rock ground to <200 mesh were dissolved in a mixture of boiling sulphuric and hydrofluoric acids. After dissolution, the Fe^{2+} was titrated against a solution of freshly standardized potassium permanganate, see Ingamells (1960). The analysis was carried out three times and the average of the best two was taken.

The Fe^{3+}/Fe^{2+} ratio of the hastingsite was determined at the Geophysical Laboratory, Carnegie Institution of Washington, by Dr. David Virgo using Mossbauer spectroscopy. For details of this technique, see Wood & Virgo (1989) and Virgo & Popp (2000).

Analyses of the hastingsite and its host rock are given in Table 1 where a comparison can be made with the riebeckite and its host rock from the Carn Chuinneag mass. Also included for comparison are compositions of the lower palaeozoic Quincy (riebeckite) and Peabody (hastingsite) granites in Massachusetts (Lyons 1972). In both regions the amphibole compositions correlate with the CaO and Al_2O_3 and the Fe^{3+}/Fe^{2+} ratios of the host rocks. The hastingsite granites are similar but the Fe^{3+}/Fe^{2+} ratio in the Quincy riebeckite granite which contains more aegirine is significantly higher than in the gneissic riebeckite granite of Carn Chuinneag. The alumina contents of the hastingsites are high relative to hastingsites from other granites (Deer *et al.* 1997). In the hastingsite from Inchbae, $[(K_{0.419}Na_{0.12})(Ca_{1.685}Na_{0.315})$ $(Al_{0.56}Ti_{0.08}Fe'''_{1.101}Fe''_{2.93}$ $Mg_{0.262}Mn_{0.057})(Si_{5.976}Al_{2.024})$ based on 23 O's], Al(vi)/Al(iv) is particularly high.

The garnet in the hastingsite gneissic granite from the Inchbae mass typically occurs in anhedral grains up to 2 mm across with many inclusions; in places it occurs in clusters of smaller grains. The average of 15 electron microprobe analyses of the garnets carried out by Dr. Jeremy Delaney at Rutgers University, gives a composition of Py 0.5, Alm 48, Spess 5, Gross 42, And 4. (after the determination of Fe^{3+}/Fe^{2+} by Mossbauer spectroscopy). Variation in a single slide is shown in Figure 2 where antipathetic relationships between CaO & MnO and Al_2O_3 & SiO_2 are evident.

Structural implications

The intrusive relationships of the hastingsite granite of Inchbae appear to be comparable to those of the riebeckite granite of Carn Chuinneag. Although limited outcrops preclude any direct evidence of the riebeckite granite having invaded the surrounding coarse grained granite, analyses of radiogenic lead from zircons indicate that the riebeckite granite was a late-stage member of the Carn Chuinneag complex (Pidgeon & Johnson 1974).

The occurrence of riebeckite (or arfvedsonite) in some members of closely related contemporaneous granite masses, and of hastingsite in others of the same group has been noted in New Hampshire and Nigeria as well as in Massachusetts (Ernst 1962, Lyons 1972). Evidently in each region where related granites occur, with riebeckite in some and hastingsite in others, different physico-chemical conditions prevailed during crystallization. This is apparent from the chemical compositions of the host rocks, CaO and Al_2O_3 being higher in the hastingsite-bearing granites, and oxygen fugacity being higher in the riebeckite granites. These differences may be due to crystallization at different temperatures and/or at different depths in the Earth's crust.

The suggestion that the Inchbae mass may underlie the Carn Chuinneag mass was made on the basis of current

TABLE 1

Analyses of alkali amphiboles and host rocks

	1	2	3	4	5	6	7	8
SiO_2	69.96	37.00	72.08	38.91	73.80	47.73	74.86	47.06
TiO2	0.23	0.66	0.35	1.89	0.23	0.72	0.20	1.53
Al_2O_3	12.71	13.6	13.08	8.51	11.90	2.61	11.61	2.36
Fe_2O_3	0.59	9.09	0.53	6.41	1.90	13.37	2.29	12.91
FeO	2.39	21.77	2.81	26.30	1.91	23.25	1.25	20.92
MnO	0.04	0.42	0.09	0.90	0.12	0.61	0.02	0.76
MgO	0.14	1.08	0.11	1.93	0.33	0.12	0.05	0.30
CaO	0.92	9.74	1.07	9.64	0.30	1.35	0.41	3.76
Na_2O	3.14	1.39	4.09	2.51	5.05	6.00	4.30	5.96
K_2O	5.53	2.03	5.30	1.14	4.93	2.12	4.64	1.22
$H_2O^{(+)}$			0.20	0.83	0.13	1.54	0.31	1.64
F				0.45		1.00		1.16
P_2O_5	0.05	0.05	0.07					
$H_2O^{(-)}$			0.08	0.95	0.04	0.02	0.04	0.28
ZrO_2					0.04			
Li_2O				0.04				0.38
sub total	95.70	96.83	99.86	100.41	100.68	100.44	99.98	100.24
less O≡F				0.19		0.42		0.49
Total*	95.70	96.83	99.98	100.22	100.68	100.02	100.18	99.75
Fe^{3+}/Fe^{2+}	0.22	0.38	0.17	0.22	0.90	0.52	1.65	0.56
Si		5.976		6.410		7.548		7.409
Al^{iv}		2.024		1.590		0.452		0.439
ΣT		8.000		8.000		8.000		7.848
Al^{vi}		0.560		0.060		0.041		0.000
Ti		0.080		0.230		0.085		0.180
Fe^{3+}		1.101		0.790		1.593		1.532
Fe^{2+}		2.930		3.620		3.063		2.755
Mg		0.262		0.470		0.028		0.070
Mn		0.057		0.130		0.085		0.101
ΣC		4.990		5.30		4.895		4.638
Li				0.030				0.240
Ca		1.685		1.700		0.228		0.634
Na		0.315		0.270		1.772		1.126
ΣB		2.000		2.000		2.000		2.000
Na		0.120		0.530		0.068		0.694
K		0.419		0.240		0.435		0.246
ΣA		0.539		0.770		0.503		0.940
OH				0.910		1.631		1.728
F				0.240		0.493		0.578

(1) Hastingsite gneissic granite. Inchbae mass. (M. J. Carr, pers. comm.)**
(2) Hastingsite from 1. (M. J. Carr, pers. comm.)***
(3) Hastingsite ('ferrohastingsite') granite, Peabody granite. (Lyons 1972)
(4) Hastingsite ('ferrohastingsite') from 3. (Lyons 1972)
(5) Riebeckite granite gneiss, Carn Chuinneag (Peach *et al.* 1912)
(6) Riebeckite from (5). (Harker 1962)
(7) Riebeckite granite, Quincy granite. (Lyons 1972)
(8) Riebeckite from (6). (Lyons 1972)

Mineral formulae are based on 23 O or 24 (O,OH,F).
*Totals after correction for fluorine and Fe^{3+}/Fe^{2+} where applicable.
**After splitting total iron into FeO and Fe_2O_3 as indicated by wet chemical analyses for FeO content.
***After splitting total iron into FeO and Fe_2O_3 as indicated by Mossbauer spectroscopy.

bedding, showing younging towards the North, observed in the psammitic rocks at the contact on Meall nan Sac at the North margin of the Inchbae mass (Harker 1956). It was assumed that the psammitic succession between the granite masses was essentially right-way-up during intrusion. Wilson & Shepherd (1979) came to the same conclusion based on a wider stratigraphic interpretation.

At the SE margin of the Inchbae mass on the West side of Meall a' Bhaird a lil-par-lit contact between the Inchbae Rock and the country rock is exposed (Fig. 3). This suggests that the SE margin of the Inchbae mass was at greater depth than any of the contacts seen around the Carn Chuinneag mass which are simple and clear-cut (Shepherd 1973).

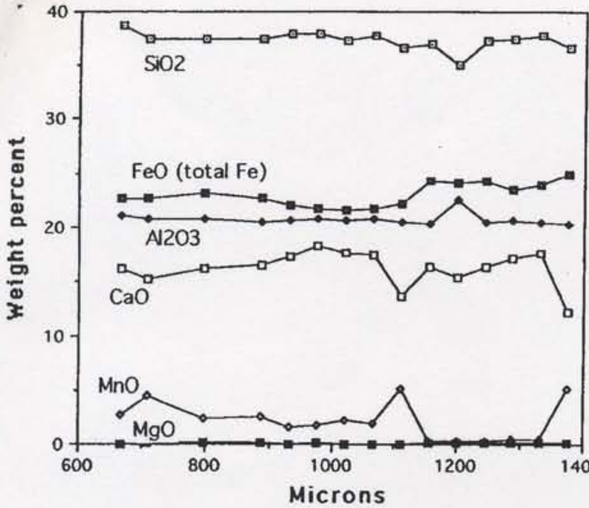

FIG. 2. Variations in the composition of garnet in hastingsite gneissic granite from Inchbae mass.

With regard to the overall configuration of the Carn Chuinneag–Inchbae complex, several theories have been proposed. Lacking evidence of significant cross-cutting relationships with the country rocks, it is generally agreed that the Carn Chuinneag mass is essentially concordant. After a survey of some of the outcrops in and around the Garbh Allt on the North side of the Carn Chuinneag mass, Shepherd (1973) concluded that the mass was sheet-like. (His data (fig. 9, loc. cit.) show current bedding younging toward the North at 250 m and 375 m to the North of the granite contact.) Subsequently, this concept was reappraised and it was suggested that the intrusion lies in the core of a synform (Wilson & Shepherd 1979). However, since the country rocks on the North side of the Carn Chuinneag mass are folded it is important to consider the direction of younging as indicated by features, such as graded or current bedding, at the margin of the gneissic granite rather than in outcrops many metres removed from it. There are at least six outcrops along the North contact of the Carn Chuinneag mass where younging is clearly in a northerly direction. An example of one of these is shown in Figure 4. There are two additional outcrops in which younging is probably to the North (Harker 1956). As far as we know, no examples of bedding, at the contact, clearly indicating younging to the South, have so far been reported.

These facts present a difficulty for a theory that the Carn Chuinneag mass lies in the core of a synclinal form.

Since the directions of younging at the North margins of both the Inchbae and Chuinneag masses have a northerly component, it appears that they are quasi-parallel at different crustal levels. This is supported now by the recognition of the hastingsite gneissic granite in the Inchbae mass and the lit-par-lit contact on Meall a' Bhaird.

Conclusions

Petrologic evidence from a newly described hastingsite gneissic granite in the Inchbae mass supports the conjecture that the Inchbae mass was intruded at a crustal depth different from that of the Carn Chuinneag mass. Remnant current bedding indicates that the Carn Chuinneag –Inchbae complex comprises two distinct intrusions with the Inchbae mass at a lower stratigraphic level than the Carn Chuinneag mass.

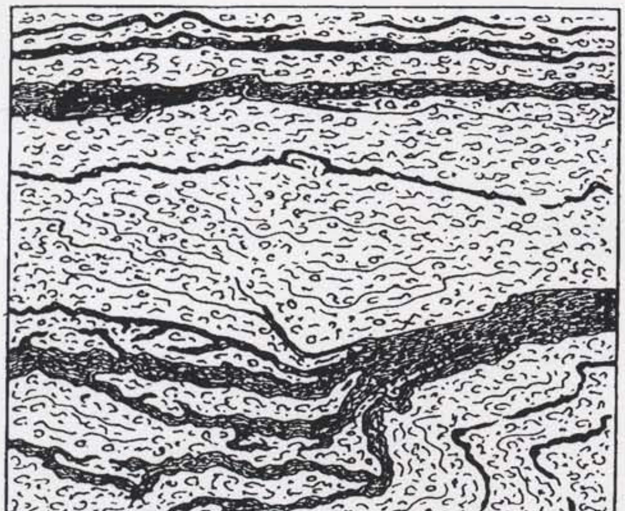

FIG. 3. Lit-par-lit contact (W flank of Meall a' Bhaird).

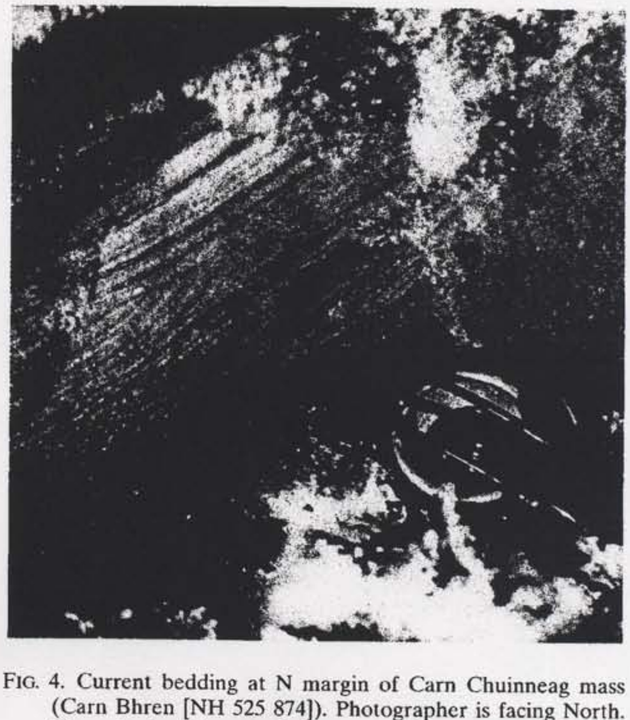

FIG. 4. Current bedding at N margin of Carn Chuinneag mass (Carn Bhren [NH 525 874]). Photographer is facing North. Current bedding indicates younging towards North. Compass 5.5 cm in diameter (for scale only).

Acknowledgements

The authors acknowledge with gratitude the assistance of the following colleagues: Dr. David Virgo (Geophysical Laboratory) for the Mossbauer analyses, Dr. Michael J. Carr (Rutgers) for the DCP emission spectroscopy analyses, Dr. Jeremy S. Delaney (Rutgers) for the electron microprobe analyses, Dr. Gene C. Ulmer (Temple) for the wet FeO analyses. This project was partly supported by a grant from the University of Pennsylvania's Nassau Fund. Dr. David Wilson reviewed the manuscript.

References

ALBEE, A. L. & RAY, L. 1970. Correction factors for electron probe microanalysis of silicates, oxides, carbonates, phosphates, and sulfates. *Analytical Chemistry* **42**, 1408–14.

BENCE, A. E. & ALBEE, A. L. 1968. Empirical correlation factors for the electron microanalysis of silicates and oxides. *Journal of Geology* **76**, 382–403.

DEER, W. A., HOWIE, R. A. & ZUSSMAN, J. 1997. *Rock-forming Minerals, Double-chain Silicates 2B*, The Geological Society, London, 242–68.

ERNST, W. G. 1962. Synthesis, stability relations, and occurrence of riebeckite and riebeckite-arfvedsonite solid solutions. *Journal of Geology* **70**, 689–736.

FEIGENSON, M. D. & CARR, M. J. 1985. Determination of major, trace and rare-earth elements in rocks using DCP-AES. *Chemical Geology* **51**, 19–27.

HARKER, R. I. 1956. The stratigraphy and folding of some metamorphosed Moine sediments around the Carn Chuinneag and Inchbae granite gneisses. *Geological Magazine* **93**, 57–62.

HARKER, R. I. 1962. The older orthogneisses of Carn Chuinneag and Inchbae. *Journal of Petrology* **3**, 215–37.

INGAMELLS, C. O. 1960. A new method for "ferrous iron" and "excess oxygen" in rocks, minerals, and oxides. *Talanta* **4**, 268–73.

JOHNSTONE, G. S. & MYKURA, W. 1989. The Northern Highlands of Scotland. *British Regional Geology* 92–5.

LYONS, P. C. 1972. Significance of riebeckite and ferrohastingsite in microperthite granites. *American Mineralogist* **57**, 1404–12.

PEACH, B. N., GUNN, W., CLOUGH, C. T., HINXMAN, L. W., CRAMPTON, C. B., ANDERSON, E. M. & FLETT, J. S. 1912. *The geology of Ben Wyvis, Carn Chuinneag, Inchbae and the surrounding country*. Geological Survey, Scotland, Memoir. No. 93.

PIDGEON, R. T. & JOHNSON, M. R. W. 1974. A comparison of zircon U-Pb and whole rock Rb-Sr systems in three phases of the Carn Chuinneag granite, Northern Scotland. *Earth & Planetary Science Letters* **24**, 105–12.

SHEPHERD, J. 1973. The structure and structural dating of the Carn Chuinneag intrusion, Ross-shire. *Scottish Journal of Geology* **9**, 63–88.

VIRGO, D. & POPP, R. K. 2000. Hydrogen deficiency in mantle-derived phlogopites. *American Mineralogist* **85**, 753–9.

WILSON, D. & SHEPHERD, J. 1979. The Carn Chuinneag granite and its aureole. *In* Wilson, D., Shepherd, J., Harris, A. L., Holland, C. H. & Leake, B. E. (eds), *The Caledonides of the British Isles – reviewed*. The Geological Society, London, 669–675.

WOOD, B.J. & VIRGO, D. 1989. Upper mantle oxidation state: Ferric iron contents of lherzolite spinels by ^{57}Fe Mossbauer spectroscopy and resultant oxygen fugacities. *Geochimica et Cosmochimica Acta* **53**, 1277–91.

MS. accepted for publication 23rd *April* 2001