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Widespread secondary Ca garnet and other Ca silicates in the Galway Granite and its satellite plutons caused by fluid movements, western Ireland

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ABSTRACT

Widespread secondary andradite-grossular-hydrogrossular garnet, epidote, prehnite and titanite occur throughout the Galway Granite and its satellite plutons (Roundstone; Inish; Omey and Letterfrack) and even in some of the country rocks several kilometres from the granites. These minerals are not found in low CaO (<1%) granites. They formed as result of secondary fluid movements which altered the biotite, plagioclase and hornblende and also produced sericite and chlorite.

KEYWORDS: andradite, grossular, hydrogrossular, epidote, hornblende, prehnite, Galway, Ireland.

Introduction

ALTHOUGH euhedral late magmatic almandine-spessartine garnets are known from late-stage granites and aplites in the Galway batholith (Wright, 1964; Leake, 1968; Whitworth and Feely, 1994), the widespread existence of secondary garnet accompanying other Ca-rich secondary silicates, epidote, prehnite and titanite, has not previously been recorded. This is despite intensive studies on the batholith over the last 40 years, including the recognition of multiple fluid

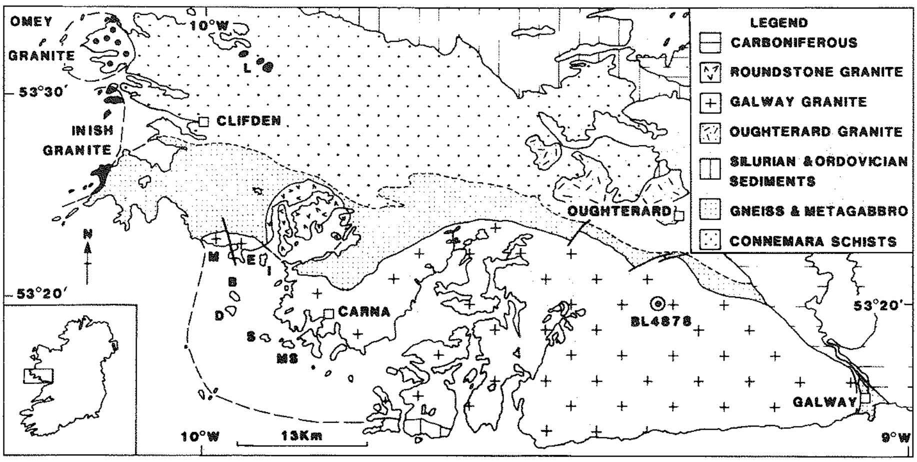

FIG. 1. Geological sketch map of Connemara, Western Ireland showing the Galway Granite and its satellite plutons of Roundstone, Inish, Omey and Letterfrack (L). B, Illaunacroagh; D, Deer Island or Croaghnakeela Island; E, Errisbeg Townland; I, Inishlackan; M, Murvey; MS, Mason Island; S, St Macdara's Island. Circled spot is location of specimen BL4878.

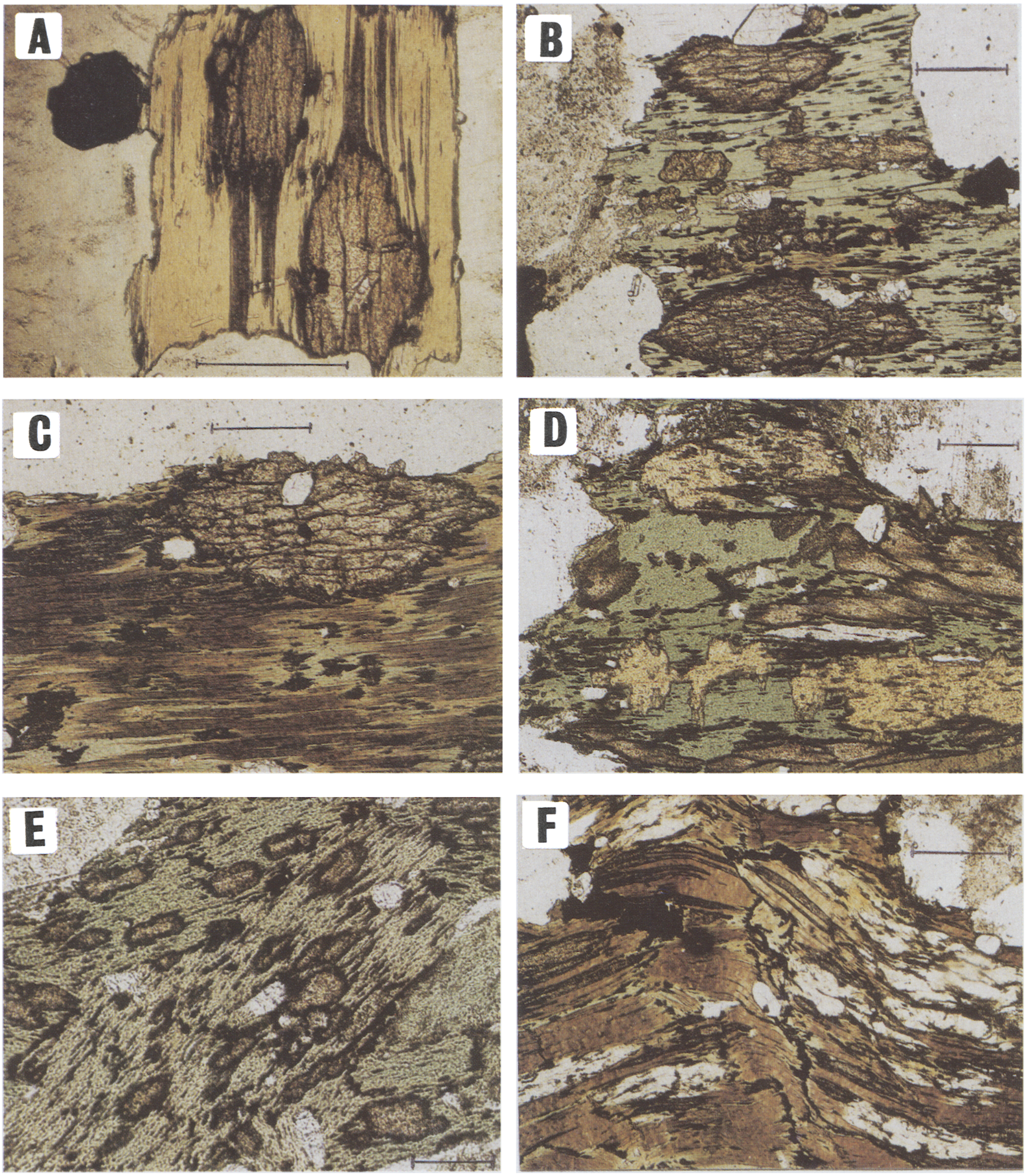

FIG. 2. Photomicrographs of secondary Ca-rich silicates in the Galway Granite. All in plane polarized light. Scale bar is 0.2 mm. (A) Garnet, with dark rims, grown in biotite and including magmatically crystallised apatite prims. Feldspar and magnetite outside the biotite. BL3334, Carna Granite, Deer Island. (B) Garnet with dark rims grown in chlorite formed from biotite. Elongated grains of epidote, lacking dark rims, occur in the centre and colourless apatite at the top and in the chlorite. Quartz, feldspar and magnetite outside the chlorite. BL3278, Carna Granite, Inishlackan. (C) Garnet in partly chloritised biotite. Note the thin strips of garnet in the biotite cleavage left of the principal garnet grain. Apatite inclusions. Quartz at the top. BL3278, Carna Granite Inishlackan. (D) Chlorite with nested garnets on the right and bottom; solitary garnet on left. Epidotes near top and bottom, hornblende in bottom right-hand corner, colourless prehnite in centre and scattered apatites. Quartz and feldspar outside chlorite. BL4878

fluxes that have passed through the Galway Granite (e.g. O'Reilly *et al.*, 1997) and the fact that similar assemblages are known in some other granites, e.g. Dartmoor, England (Alderton, 1988).

Mineralogy

The main bulk of the Galway batholith (Fig. 1) is a rock containing quartz, oligoclase, andesine, K-feldspar, biotite, hornblende, titanite, apatite, magnetite and zircon, in which the plagioclase is partly sericitised, kaolinised and epidotised, especially in the more calcic cores; the biotite is partly chloritised, the hornblende variably altered to chlorite or chlorite plus epidote, and the titanite is partly altered to leucoxene (Leake, 1974; El Desouky *et al.*, 1996). In a great many samples partly or completely chloritised biotite contains thin strips, lenses or bulbous grains of near colourless to very faintly brown garnet which reaches a maximum of 0.2 mm in diameter (Fig. 2). Occasionally the garnet occurs at the edge of the biotite, or in otherwise fresh biotite, i.e. not chloritised. It is often slightly anisotropic and sometimes displays traces of complex twinning; the refringence is near to, or above 1.80 but the presence of a thin skin of dark material at the edge of many of the grains exaggerates the apparent refringence. Many of the chlorites and biotites also contain lenses of prehnite, replacive epidote and grains of secondary, anhedral titanite, which contrasts with the euhedral primary magmatic titanite. All these secondary minerals occur in the Errisbeg Townland, the Megacrystic, the Carna, the Cuilleen and other granite types except the low Ca (CaO <1%) varieties such as the late Murvey granite types, right across the batholith from Deer Island, Errisbeg Townland, Inishlackan, Illaunnacroagh, St MacDara's Island, Mason Island and Carna in the west to the environs of Galway in the east and also throughout the Roundstone (Leake and Tanner, 1994), Omey, Inish and Letterfrack (Townend, 1966) Granites, (Fig. 1).

Electron microprobe analyses of the minerals in a typical sample of the Megacrystic Granite from the centre of the Galway Granite (Fig. 1), BL 4878 are given in Table 1. The average garnet composition, with little variation from grain to grain, is 54.4 mol. % andradite, 30.3% grossular, 14.1% hydrogrossular and 1.2% spessartine assuming all the Fe is present as Fe_2O_3 and that the H_2O present is exactly enough to make the analysis total equal 100.00. Although there is some variation among different samples, this composition is quite typical. The edges of the grains, when darker, are slightly richer in TiO_2 (up to at least 2%) but otherwise no systematic zoning has been detected.

The change from biotite to chlorite shows the usual loss of Ti, K and some Si but the relative percentages of Al_2O_3: FeO: MgO in the biotite (32: 45: 23) are closely similar to those in the chlorite (29: 45: 26) suggesting that little movement of Al, Fe or Mg took place, so the main chemical change was loss of K, Ti, and some Si in exchange for H_2O. The Ca in the secondary garnet, epidote, prehnite and titanite must have been obtained largely from the altered calcic cores of the plagioclase and to a small extent from the chloritisation of the hornblende which is often not greatly altered; the Ti for the titanite from the biotite and the K for the sericitic replacement of the plagioclase is also from the biotite. Some of the garnets are grown in chlorite which appears to replace hornblende but is probably chlorite formed from biotite which had earlier replaced the hornblende.

The blue-green hornblende sometimes shows slight zoning with a marked decrease in Ti, a small decrease in Mg and a small increase in Fe in passing from the centre to the edge of the grains - trends consistent with magmatic fractionation. Using the calibration of Hammarstrom and Zen (1986), the ferro-edenite (Leake *et al.*, 1997) in the sample yields a pressure of crystallization of 3.93 ± 0.58 kbar, based on the total Al per 23 oxygens, the core and margin having identical total Al of 1.56. This pressure is similar to that of 4.39 ± 0.52 kbar obtained by Leake and Ahmed Said (1994) using the same calibration, from a sample about 2 km from the present sample. Some of the grains have, in part, a minute outer skin of pale ferro-actinolite (analysis 3) which has

(analysed sample), Megacrystic Granite. (E) Garnet grains with dark rims and colourless apatite in chlorite. BL4981, Megacrystic Granite, Glenicmurrin. (F) Prehnite lenses in biotite with thin strips of garnet on each side of the magnetite clot. Quartz and feldspar outside biotite. Apatite crystal in centre of biotite. BL4980, Megacrystic Granite, Glenicmurrin.

TABLE 1. Chemical analyses of minerals in Galway Granite specimen BL4878

	1	2	3	4	5	6	7	8	9	10
SiO_2	43.90	43.64	51.33	35.99	27.50	36.45	36.66	30.49	42.41	33.69
TiO_2	1.30	0.72	0.06	3.27	0.08	0.17	0.20	36.52	0.00	1.08
Al_2O_3	8.70	8.60	5.45	14.71	17.38	20.16	20.73	1.48	22.45	9.52
tFe_2O_3						17.93	17.21	1.69	3.19	17.80
tFeO	18.92	20.10	17.86	20.68	26.73					
MnO	0.76	0.72	1.59	0.46	0.59	0.55	0.24	0.15	0.07	0.57
MgO	10.06	9.09	9.07	10.75	16.30	0.00	0.00	0.00	0.00	0.00
CaO	11.89	12.12	11.98	0.01	0.09	22.85	23.21	28.48	26.78	34.19
Na_2O	1.29	1.17	0.30	0.12	0.08					
K_2O	0.98	0.94	0.18	9.45	0.10					
H_2O	(1.96)	(1.94)	(1.95)	(3.89)	(11.21)	(1.89)	(1.75)		(4.50)	(3.13)
Total	99.76	99.04	99.77	99.33	100.02	(100.00)	(100.00)	98.81	99.30	(100.00)
Number of ions on the basis of										
		24(O,OH)			36(O,OH)	12.5(O)		4Si	24(O,OH)	24(O)
Si	6.68	6.73	7.57	5.55	5.81	2.96	2.96	4.00	5.92	5.265
^{IV}Al	1.32	1.27	0.43	2.45	2.19	0.04	0.04	0.00	0.08	0.814*
^{VI}Al	0.24	0.29	0.52	0.22	2.13	1.89	1.94	0.23	3.61	1.755
Ti	0.15	0.08	0.01	0.38	0.01	0.01	0.01	3.60	0.00	0.131
Fe^3						1.10	1.05	0.17	0.33	2.093
Fe^2	2.40	2.59	2.19	2.66	4.71					
Mn	0.10	0.09	0.19	0.05	0.10	0.04	0.01	0.01	0.01	0.075
Mg	2.28	2.08	2.12	2.47	5.12	0.00	0.00	0.00	0.00	0.000
Ca	1.94	2.00	1.89	0.00	0.03	1.98	2.01	4.00	4.00	5.725
Na	0.38	0.35	0.09	0.04	0.03					
K	0.19	0.18	0.03	1.86	0.03					
OH	(1.98)	(1.99)	(1.91)	(4.00)	(15.77)	(1.02)	(0.94)		(4.19)	
ΣT	8.00	8.00	8.00	8.00	8.00	3.00	3.00	4.00	6.00	6.08
ΣC	5.00	5.00	5.00	5.78	12.16	3.00	3.00	4.00	3.95	3.98
ΣB	2.00	2.00	2.00	1.90		2.02	2.02	4.01	4.00	5.80
ΣA	0.68	0.66	0.04							
										*OH/4

1. Ferro-edenite (Leake *et al.*, 1997) centre of calcic amphibole.
2. Ferro-edenite (Leake *et al.*, 1997) edge of above calcic amphibole.
3. Ferro-actinolite (Leake *et al.*, 1997) pale fringe of above amphibole, where developed.
4. Biotite.
5. Chlorite formed by alteration of above biotite.
6. Centre of epidote in chlorite. H_2O by difference from 100%. $100Fe^{3+}/(Fe^{3+} + Al) = 36.3\%$.
7. Edge of epidote. H_2O by difference from 100%. $100Fe^{3+}/(Fe^{3+} + Al) = 34.6\%$.
8. Euhedral magmatic titanite.
9. Prehnite in chlorite.
10. Andradite (54.4 mol.%) – grossular (30.3 mol. %) – hydrogrossular (14.4 mol. %) – spessartine (1.2 mol.%). H_2O assumed to make total 100.00; all Fe assumed to be Fe_2O_3. Garnet grown in chloritised biotite.

Note. All H_2O assumed or calculated. Total iron allocated 100% to either Fe_2O_3 or FeO. All analyses are the average of at least four minerals with four analysed spots per mineral determined on a Camebax SX50 electron microprobe in the Department of Geology and Applied Geology, University of Glasgow, using the standards and conditions specified in Leake and Ahmed Said (1994). Typical plagioclase is $An_{25}Ab_{74}Or_1$. BL4878 comes from 440 m south of the south point of Lough Glenn in Letter, on 1:10,560 Sheet 67, Co. Galway.

a sub-solidus composition and is not magmatic in crystallization because it falls outside the field of magmatic calcic amphibole (Leake, 1971). Such compositions have been noted before in the western part of the Galway batholith by Leake and Ahmed Said (1994) so there is wide distribution of this late-stage actinolite or ferro-actinolite. The recognition of extensively dispersed secondary garnet, prehnite and epidote in the Galway Granite suggests that the actinolite–ferro-actinolite fringes to the magmatic hornblende are also part of this secondary phase of growth of Ca-rich minerals.

Secondary titanite is rare in sample 4878, so analyses are not included, but according to Tulloch (1979), who has described a similar development of secondary garnet, epidote, prehnite and titanite (but with pumpellyite in addition) in the Victoria Range granitoids, and in other granitoids throughout the Tasman metamorphic belt of S. Island, New Zealand, the secondary titanite should be rich in Al. It can be predicted that it should also be much lower in Nb than the magmatic titanite.

The epidote is distinctly rich in Fe and is similar to the compositions of epidote reported by Tulloch (1979) in biotite and chloritised biotite. In many of the granite samples a little euhedral zoned allanite is also a secondary mineral.

Discussion

Although the principal development of the chlorite-prehnite-epidote-Ca garnet assemblage is in the 400 Ma granite suite, the same assemblage has been found in hornblende–biotite–plagioclase metagabbros and amphibolites with chloritised biotite and sericitised and saussuritised plagioclase outside the Galway Granite in the country rocks up to at least 8 km from the granite. This supports the conclusions of Jenkin *et al.* (1992) based on D/H and $^{18}O/^{16}O$ studies that widespread secondary alteration in Connemara is caused by a hydrothermal convection system related to the cooling of the Galway Granite suite. Three major episodes of fluid movement have subsequently been identified in the Galway Granite by O'Reilly *et al.* (1997). The earliest of these was at high temperature (perhaps 600°C) and 1–3 kbar pressure and was essentially magmatic fluid but extended down to 300–390°C (O'Reilly *et al.*, 1997). In this episode the growth of the actinolite probably occurred. The second fluid was of meteoric origin and ranged from 270 to 340°C.

Without further analyses it is uncertain whether the chlorite-prehnite-epidote-garnet-titanite assemblage is an equilibrium one or one grown over a range of temperatures as seems most likely. Grandites are known to grow from below 200°C (Easton *et al.*, 1977) to above 600°C; prehnite is stable up to a maximum of 400°C (Liou *et al.*, 1983) and Fe-rich epidote suggests a temperature below 350°C but P_{fluid} and f_{O_2} also influence prehnite, epidote and garnet compositions (Liou *et al.*, 1983). Chlorite has a wide stability range. Probably the two major fluid-circulation episodes were responsible for the secondary minerals described. Such widespread fluid circulation was also responsible for the scatter of hornblende, biotite and muscovite K-Ar and Rb-Sr ages between 490 and 390 Ma in the Connemara schists, metagabbros and gneisses (Elias *et al.*, 1988; Miller *et al.*, 1991) suggestive of the influence of high temperature (300–500°C) fluids in partly opening the isotope systems in these minerals.

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