MINERALOGICAL MAGAZINE

VOLUME 44 NUMBER 334 JUNE 1981

Contact metamorphism and fluid movement around the Easky adamellite, Ox Mountains, Ireland

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ABSTRACT. Contact metamorphism in the aureole of the Easky adamellite produced andalusite at the expense of regional staurolite, kyanite, and garnet. In the inner aureole sillimanite and K-feldspar also grew. Cordierite is only rarely present. Conditions of metamorphism in the inner aureole have been deduced from five independent criteria as 595 ± 30 °C and 2.5 ± 0.5 kb. The nearby Lough Talt adamellite was emplaced at slightly higher pressures. Some aureole rocks have undergone oxidation with conversion of regional garnet to magnetite and andalusite. The reacting assemblage buffered f_{O_2} near 10^{-17} bars. It is inferred that oxidation was caused by movement of H_2O from the country rocks into the intrusion.

THE central and south-western parts of the Ox Mountains inlier of Counties Mayo and Sligo comprise an elongate belt of metasedimentary rocks with subordinate metabasites believed by us to be Dalradian (Lemon, 1971; Long and Yardley, 1979) and intruded by the Slieve Gamph Igneous Complex (Taylor, 1968), chiefly comprising the Ox Mountains granodiorite (Max *et al.*, 1976). The main part of the complex (fig. 1) has no obvious thermal aureole, although Phillips and Andrews (1977) have reported one occurrence of fibrolite. For the most part the envelope rocks are regionally metamorphosed psammites and semipelites (Long and Max, 1977) that are unlikely to be very responsive to further heating, however the granodioritic rocks have undergone some pervasive deformation and retrograde metamorphism and it may be that the relative lack of contact effects could result from intrusion into rocks still hot from regional metamorphism, or from relatively cool tectonic emplacement (although there are many minor dyke intrusions along the SE margin).

At the NE end of the complex is the Lough Talt adamellite (fig. 1) which is less deformed and extends beyond the main complex into pelitic country rocks in which thermal andalusite and sillimanite have developed, overprinting regional staurolite grade assemblages. There is a further adamellite pluton 9 km to the northeast, the Easky adamellite, that also has a well-developed thermal aureole superimposed on the regional staurolite-kyanite zone (Yardley *et al.*, 1979).

The Slieve Gamph Igneous Complex has been dated at 487 ± 6 Ma by Pankhurst *et al.* (1976), and the granodiorite portion at 500 ± 18 Ma by Max *et al.* (1976). It seems possible that the two adamellite plutons are younger than the rest of the complex because of their relative lack of deformation, the cross-cutting relationships of the Lough Talt body and because a single sample from the Easky adamellite analysed by Pankhurst *et al.* (1976) fell significantly below the isochron for other samples.

This paper is principally concerned with the metamorphism around the Easky adamellite. The geology of the region has recently been described by Andrews *et al.* (1978) and the outline of the

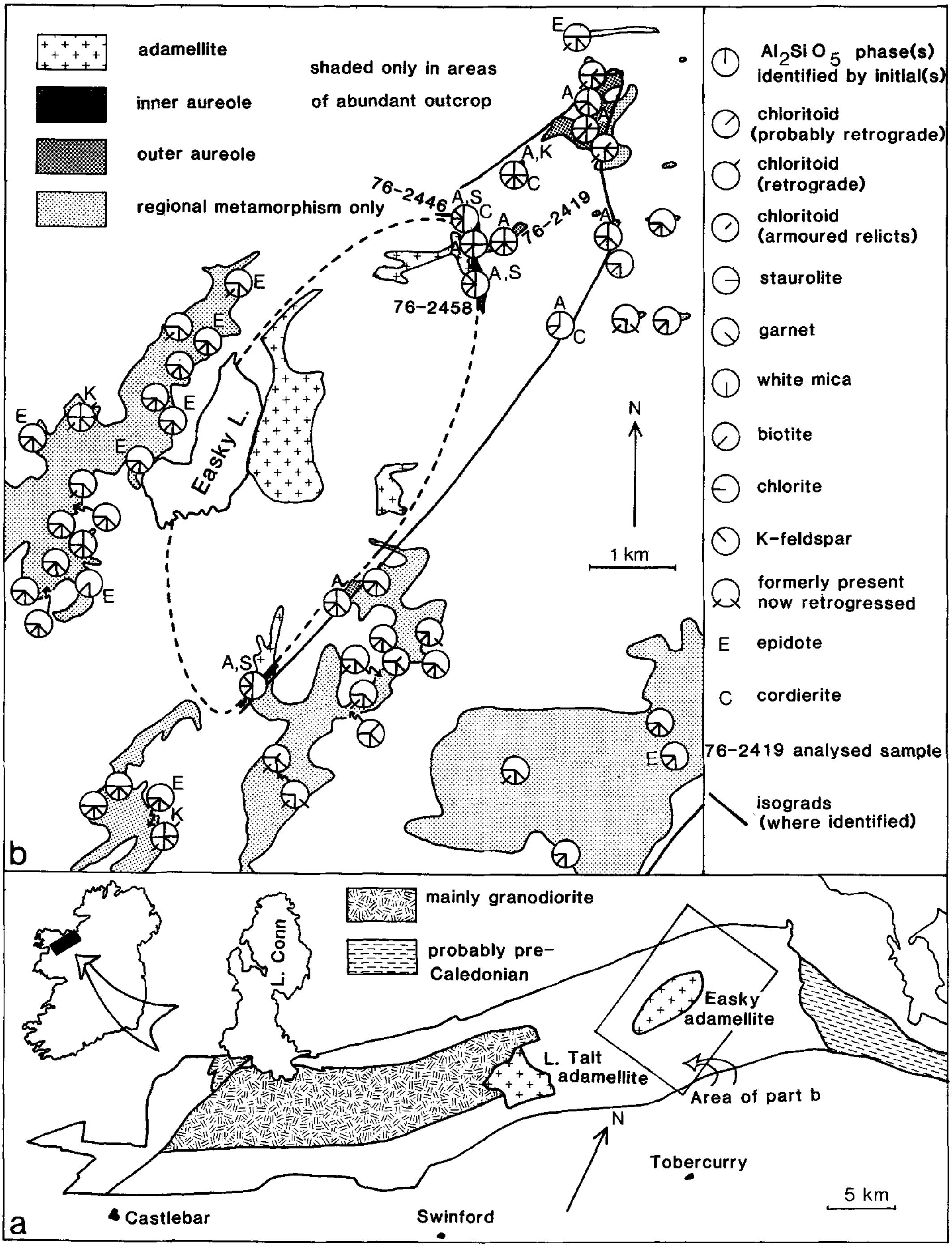


FIG. 1. (*a*) Sketch map showing the Slieve Gamph Igneous Complex in relation to the Ox Mountains inlier. (*b*) Regional and contact metamorphic assemblages in the vicinity of the Easky adamellite.

intrusion and aureole are shown in fig. 1*b*. Much of the area is bog covered and poorly exposed, but there are two areas where the contact is seen and where zonation in the aureole can be mapped. The lack of major contact effects at the western margin suggests that it could be faulted, however a zone with reddish biotite does occur next to the contact here, and may reflect mild contact metamorphism.

Contact metamorphic effects

The aureole is largely developed in pelitic rocks which have the regional assemblage staurolite ± kyanite + garnet + biotite + muscovite ± chlorite + plagioclase + quartz + rutile *or* ilmenite. These have sometimes undergone regional retrogression with production of epidote, chlorite, chloritoid, albite, and the white micas muscovite, paragonite, and margarite (Yardley *et al.*, 1979). It is most likely that this retrogression predates the intrusion of the adamellite. The principal mineralogical changes resulting from contact metamorphism in the Easky aureole are:

(*a*) breakdown of staurolite and garnet (and kyanite where present);

(*b*) growth of andalusite and, in the inner aureole only, K-feldspar and sillimanite (fibrolite). Cordierite was also rarely produced but is now largely pinitized;

(*c*) in the andalusite zone and in places outside it, biotite is sometimes reddish brown in colour, and this may also be a contact metamorphic effect. Typical contact assemblages (+ quartz + plagioclase) in the outer aureole are:

(1) andalusite + biotite + muscovite + staurolite + garnet + ilmenite;

(2) andalusite + biotite + muscovite + staurolite + garnet + magnetite; and in the inner aureole:

(3) sillimanite + andalusite + K-feldspar + biotite + muscovite + ilmenite (staurolite as armoured relicts in andalusite only).

Garnet and staurolite in assemblages (1) and (2) are more or less corroded and may be absent. Assemblage (1) typically has a brownish or red-brown biotite whereas in assemblage (2) the biotite is green. Magnetite in assemblage (2) occurs in complex pseudomorphs after regional garnet (fig. 2) and the same rocks may retain regional rutile in the matrix. Details of the assemblages and their distribution are shown in fig. 1*b*.

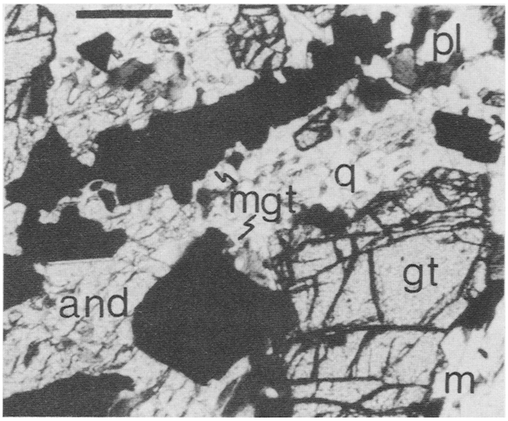
Reactions in the aureole. Production of assemblage (1) in the outer aureole can be ascribed to the reactions:

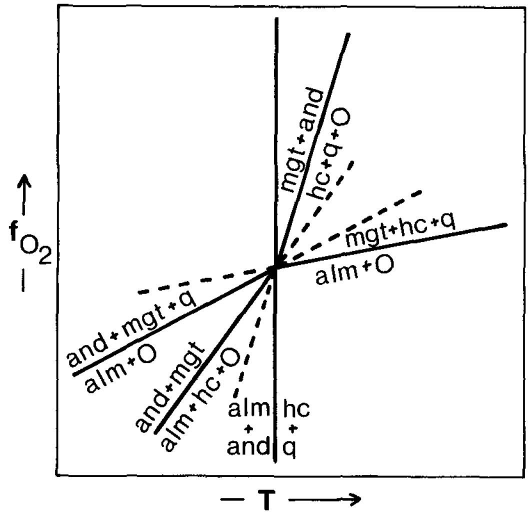
$$\text{staurolite} + \text{muscovite} + \text{quartz} \rightarrow \text{biotite} + \text{andalusite} + H_2O \qquad \text{(i)}$$

$$\text{garnet} + \text{muscovite} \rightarrow \text{biotite} + \text{andalusite} + \text{quartz} \qquad \text{(ii)}$$

Whereas (i) is principally sensitive to T, the vapour-absent reaction (ii) is strongly pressure dependent and probably reflects a drop in P between regional and contact metamorphism. The inner aureole is defined by the reaction:

$$\text{muscovite} + \text{quartz} \rightarrow \text{K-feldspar} + \text{sillimanite} + H_2O \qquad \text{(iii)}$$





FIGS. 2 and 3. FIG. 2 (left). Photomicrograph of part of a complex pseudomorph within an original regional garnet. Some garnet relicts remain (gt) but the garnet is being replaced by magnetite (mgt), andalusite (and), quartz (q), plagioclase (pl), and micas (m). Scale bar 0.5 mm, sample 76-2419. FIG. 3 (right). Schematic isobaric T-f_{O_2} diagram illustrating relationships between almandine (alm), andalusite, hercynite (hc), magnetite and quartz.

The pressure of contact metamorphism is therefore rather precisely bracketed since reactions (i) and (ii) occur in the stability field of andalusite, whereas (iii) occurs in the sillimanite field. At the present time, however, the calibration of this bracket is less certain. The Lough Talt adamellite must have been emplaced at slightly higher pressures since sillimanite appears while muscovite is still stable.

Assemblage (2) results from the breakdown of garnet by oxidation:

$$\text{almandine} + O_2 \rightarrow \text{quartz} + \text{magnetite} + \text{andalusite} \qquad \text{(iv)}$$

all three product phases have been found replacing garnet, together with plagioclase which may form from the grossular component of the decaying garnet (fig. 2). Hsu (1968) carried out experiments on the oxidation of garnet by the reaction:

$$\text{almandine} + O_2 \rightarrow \text{quartz} + \text{magnetite} + \text{hercynite} \qquad \text{(v)}$$

It can be seen from the isobaric T–f_{O_2} diagram (fig. 3) that reaction (iv) is a lower temperature alternative to reaction (v) that will occur when almandine + andalusite are stable relative to hercynite + quartz.

Conditions of contact metamorphism

We have attempted to determine the PT conditions of the inner aureole of the Easky adamellite by a variety of methods based on detailed studies of two samples, 76-2446 and 76-2458 (Geological Survey of Ireland collection). Four independent methods each produce a PT curve, plotted in fig. 5, and these should ideally intersect at a single point representing the conditions of contact metamorphism, provided all methods refer to the same episode of crystallization. In addition, the Al_2SiO_5 phase relations constrain the conditions determined for the inner aureole to lie within the sillimanite field but close to the andalusite field. Microprobe data for this study were obtained at Manchester and Cambridge Universities; both machines utilise an energy-dispersive analysing system. The compositions of the major silicate phases are given in Tables I-III.

Fluid-inclusion studies. Both samples have thin (2–5 mm) veinlets of quartz containing numerous small ($\simeq 10\,\mu$m) fluid inclusions. The quartz grains are also speared with fine needles of sillimanite, thereby confirming that they recrystallized during contact metamorphism. An estimate of fluid composition is essential for calculations based on dehydration equilibria, and cooling runs made with a Linkam heating-freezing stage show that the included fluid is H_2O with a freezing temperature (T_f) = -1 ± 0.5 °C. The slight freezing point depression is equivalent to only a 0.3M NaCl solution (Potter *et al.*, 1978) and we therefore treat the metamorphic fluid as pure H_2O. Heating runs to determine the density of individual inclusions from their homogenization temperature (T_h) permit the construction of isochores that are PT curves representing the possible conditions of entrapment of the inclusion (Touret, 1977). Inclusions in the samples studied display a wide range of T_h values

TABLE I. *Feldspar analyses for the Easky hornfelses*

	Inner aureole				Outer aureole		
	76-2446		76-2458		76-2419		
					matrix plag.		
	plag.	k-fsp core	plag.	k-fsp core	core	rim	after gt
SiO_2	58.41	64.35	61.38	64.98	65.20	63.31	62.74
Al_2O_3	26.26	18.71	24.68	18.79	22.06	22.81	24.18
CaO	7.95	—	6.38	—	2.70	3.84	4.81
FeO	0.20	—	0.31	—	—	0.22	0.34
BaO	—	1.49	—	0.37	—	—	—
Na_2O	6.67	1.55	7.77	1.79	9.69	9.17	8.61
K_2O	0.18	13.65	0.19	14.25	0.08	0.14	0.22
Total	99.67	99.75	100.71	100.18	99.85	99.49	100.90

— = below detection limit.

TABLE II. *Analyses of micas from the Easky hornfelses*

	Inner aureole				Outer aureole			
	76-2446		76-2458		76-2419			
					matrix		after gt.	
	musc.	bio.	musc.	bio.	musc.	bio.	musc.	bio.
SiO_2	46.02	35.29	45.63	35.57	45.33	34.37	44.05	34.30
TiO_2	0.85	3.14	0.76	3.04	0.36	1.99	0.81	1.89
Al_2O_3	34.25	19.45	34.29	19.31	34.58	19.19	34.16	19.94
FeO	2.60	20.60	2.84	23.25	2.62	23.20	4.65	23.31
MgO	0.32	6.70	0.23	6.29	0.34	7.04	0.72	7.43
MnO	—	—	—	0.23	—	—	—	0.14
Na_2O	0.30	—	0.41	—	0.62	—	0.60	—
K_2O	10.21	9.53	10.50	9.58	9.44	8.69	9.15	9.04
Total	94.55	94.71	94.66	96.27	93.29	94.48	94.14	96.05

— = below detection limit.

TABLE III. *Analyses of aluminosilicate and oxide minerals, oxidized pelite 76-2419*

	Garnet			Staurolite		And.	Oxides	
	core	rim A	rim B	core	rim		after gt.	matrix
SiO_2	37.53	37.49	37.51	54.53	54.90	61.88	n.d.	n.d.
TiO_2	—	0.13	0.11	0.40	0.54	—	—	93.81
Al_2O_3	21.30	20.83	21.56	27.48	27.02	36.99	n.d.	n.d.
CaO	5.80	5.95	2.88	—	—	—	n.d.	n.d.
FeO	32.35	30.87	36.61	11.70	11.87	1.43	92.25*	4.01
MgO	0.55	0.86	2.22	1.03	0.66	—	—	—
MnO	4.03	4.40	0.15	0.21	0.22	—	—	—
ZnO	n.d.	n.d.	n.d.	1.79	1.87	n.d.	n.d.	n.d.
Total	101.56	100.62	101.04	97.14	97.08	100.30	92.25*	97.82

— = below detection limit; n.d. not determined; *totals 99.10 as Fe_3O_4. Garnet 'core' is a relict near centre of original gt., 'rim A' is present corroded margin to core relict, 'rim B' is relicts from 300 μm wide marginal region to original garnet.

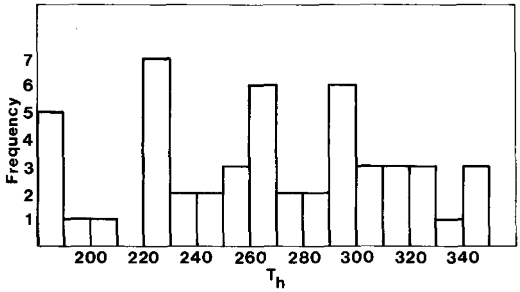


FIG. 4. Histogram of observed T_h values for H_2O fluid inclusions, samples 76-2446 and 76-2458.

(fig. 4), although certain peaks are present. The sampling is biased towards the low-density (high T_h) inclusions, since these are most likely to reflect the maximum conditions of metamorphism; low T_h inclusions are much more common than indicated but often occur as planes of secondary inclusions that are clearly late. Anomalously high T_h values can be produced by 'necking' of an original inclusion into two smaller ones, but there are a number of inclusions with $T_h \simeq 340\,^\circ C$ that show no evidence for necking. These are therefore taken as representing the metamorphic maximum, lower values probably being produced by recrystallization during cooling, and the isochore is plotted on fig. 5.

Distribution of Na between muscovite and plagioclase. The Na contents of muscovite and plagioclase are related by the equilibrium:

$$\underset{\text{In muscovite}}{NaAl_3Si_3O_{10}(OH_2)} + \underset{\text{quartz}}{SiO_2} = \underset{\text{In plagioclase}}{NaAlSi_3O_8} + \underset{\text{sillimanite}}{Al_2SiO_5} + H_2O$$

An equilibrium constant for this reaction has been determined from experimental results in the pure system by Chatterjee (1972) (Yardley *et al.*, 1980) and has been used to calculate a *PT* curve for the muscovite and plagioclase rim compositions observed. Activity coefficients (γ) for paragonite in muscovite were calculated from the data of Eugster *et al.* (1972), while γ^{ab}_{plag} was assumed to be 1.

Distribution of K between muscovite and K-feldspar. Similarly the composition of these phases is linked by the equilibrium:

$$KAl_3Si_3O_{10}(OH)_2 + SiO_2 = KAlSi_3O_0 + Al_2SiO_5 + H_2O$$

The *PT* curve for coexistence of the observed muscovite and K-feldspar compositions was calculated assuming ideal solid solution using the data of Helgeson *et al.* (1978), which allows a choice of an equilibrium structural state of K-feldspar. The method is that of Skippen (1977).

Two-feldspar thermometry. The *PT* curve shown in fig. 5 is from the calibration of Powell and Powell (1977). Two significant sources of uncertainty exist here. First, the thermometer is very sensitive to K-feldspar composition in the range present here, so that between-grain variation leads to large ($\pm$25 deg.) uncertainties in *T*, and secondly the small size of the K-feldspar grains means that cation diffusion during cooling may cause significant Na loss from them; zoning studies with the microprobe do show Na-depleted margins to K-feldspar grains.

Summary. The *PT* curves generated do not all intersect at a single point but indicate that conditions for the inner aureole attained a maximum at 595 ± 30 °C, 2.5 ± 0.5 kb. This corresponds to a depth of emplacement of around 8 km.

Oxidation reactions in the thermal aureole

Several specimens of hornfels from the outer aureole have green biotites and show breakdown of garnet to magnetite [assemblage (2)]. Since some garnet remains the mineral assemblage acts as an f_{O_2} buffer, so that having estimated *P* and *T* it is possible to calculate f_{O_2}. Although reaction (iv) has not been studied experimentally, requisite data have been extracted from the experiments of Hsu (1968) by Zen (1973), Froese (1973), and Hutcheon (1979). In this study we have used the equilibrium constant for reaction (iv) calculated by Hutcheon (1979), corrected for the structural state of Al_2SiO_5 (extracted from fig. 5). Taking *P* 2.5 kb, *T* 580 °C

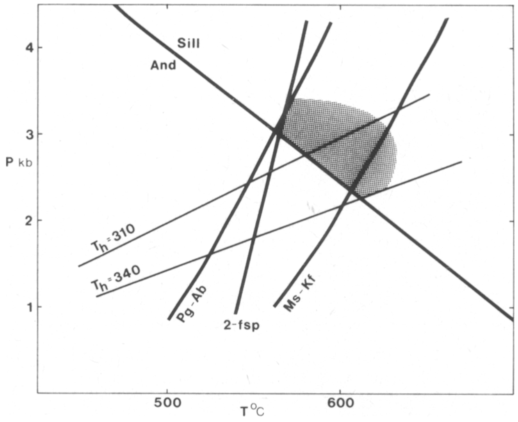


FIG. 5. *PT* diagram showing probable conditions in the inner Easky aureole (stippled region). Andalusite–sillimanite boundary based on data of Holdaway (1971). Light lines are isochores for fluid inclusions from data of Burnham *et al.* (1969). Heavy lines are curves calculated from the compositions of coexisting feldspars and muscovite and feldspar (see text).

for the outer aureole and $X_{gt}^{alm} = 0.794$ (Table III) gives f_{O_2} 9.7×10^{-18} bars for sample 76-2419. This is higher than would normally be expected for rocks of this grade and, together with the textural observations of replacement of almandine by magnetite, indicates that the rocks have undergone extensive oxidation.

There are two main ways in which such oxidation could be achieved: flow of H_2O through the rock up a thermal gradient (i.e. towards the intrusion) or diffusion of H_2 out of the oxidized rocks. There is insufficient evidence from the Easky aureole itself to discriminate between these possibilities, but evidence from other areas suggests that the former process may be important in thermal aureoles. Taylor (1977) has reviewed oxygen and hydrogen isotope studies that show numerous examples of interaction between granites and country rock fluids. It has been pointed out (Brown and Fyfe, 1969) that granite magmas must be deficient in H_2O in order to rise in the crust, and they will therefore tend to take up water from the country rocks. Further evidence of the movement of H_2O into granitic plutons comes from the desilication of aureole rocks. Thus the rather similar aureole of the Omey granite in Connemara (Ferguson and Harvey, 1979) actually contains corundum-bearing assemblages indicating leaching of SiO_2, and this is again compatible with the movement of H_2O into the granite, though of course corundum hornfelses may also originate by other mechanisms, such as incongruent melting. We conclude that the Easky adamellite is likely to have been emplaced as an H_2O-undersaturated magma, and to have taken up water from the country rocks while it crystallized.

Acknowledgements. This study was initiated while B.W.D.Y. was on the staff of the University of Manchester. We are grateful to Drs. N. Charnley and J. V. P. Long for providing microprobe facilities at Cambridge University. Equipment for fluid inclusion studies was provided by N.E.R.C. grant GR3/3480. This paper is published by permission of the Director, Geological Survey of Ireland.

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[*Manuscript received 10 June 1980;*
revised 21 September 1980]