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Radioelement geochemistry of Irish granites

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ABSTRACT. Data for U, Th, and K, determined by neutron activation analysis, in 128 rock samples from 14 Irish Caledonian and Tertiary granite plutons are summarized. Irish Newer Caledonian granites (ninety-four samples) have values of radioelements (average 3.6 ppm U, 12.1 ppm Th, and 3.4% K) consistent with derivation from a source of broadly uniform composition. U mineralization occurs in the voluminous and forcefully emplaced Main Donegal and Leinster plutons whereas smaller passively emplaced granites (Galway, Barnesmore, Rosses) lack mineralization. Irish Tertiary granites (thirty-four samples), which represent small batches of highly fractionated acid magmas, show moderate or high radioelement contents (11.5 ppm U, 39.9 ppm Th, 4.5% K) but are not mineralized. It is concluded that the use of elevated radioelement contents as a criterion of granite 'fertility' may be misleading in the British Isles Caledonian Province. The radioelement chemistry of granites may reflect their source composition more closely than expected for differentiated and/or contaminated acid melts.

A CAR-BORNE reconnaissance radiometric survey of the Irish Republic in 1977 identified total γ anomalies associated with certain Irish Caledonian and Tertiary granite plutons (O'Connor, 1981). A further study was undertaken to assess the potential of the granites as a source of leachable U and 128 rock samples from 14 plutons were analysed for U, Th, and K by epithermal neutron activation analysis. The data are used here to compare the radioelement chemistry of possible subduction-related plutons (Caledonian) with those related to the opening of the North Atlantic (Tertiary).

Several accounts of the abundance and distribution of radioelements in British Caledonian granites have recently been reported. Bowie *et al.* (1973) and Simpson *et al.* (1976, 1979) have provided data on the distribution of U in some of the Newer granites of Scotland, and data on U and Th contents in 194 rock samples from Scottish granites have been reported by Hennessy (1979). Data for some of the Tertiary granites, notably Skye, Mourne, and Lundy, have also been published (Moorbath and Welke, 1968; Tammemagi, 1976).

Irish granites

Caledonian plutons. Reviews of the geological setting of Irish Caledonian granites are given in Brindley (1969), Pitcher and Berger (1972), Leake (1978), and Pankhurst *et al.* (1981). Collectively, the granite plutons cover an area of over 4000 km^2 and about twenty-five separate plutons are represented (fig. 1). Individual plutons range in size from 5 to 500 km^2 and most are dome-like masses usually extending to depths of 4-10 km (Thirlaway, 1951; Cook and Murphy, 1952; Young, 1974). The major granite plutons of Leinster, Connemara, and Donegal are emplaced in a Caledonian basement succession which outcrops around the margins of the Upper Palaeozoic sedimentary cover of Central Ireland (fig. 1).

The plutons are mainly calc-alkaline, ranging in composition from diorite and granodiorite to granite. The largest plutons are dominantly granitic in composition (e.g. Leinster, Galway). With the exception of the Carnsore granodiorite, which was emplaced in Precambrian gneisses of the Rosslare complex of southeastern Ireland, the Irish Caledonian granites are located in high-grade Moine or Dalradian metasediments (northern Orthotectonic Caledonides) or in Lower Palaeozoic metasediment-metavolcanic sequences (southern Paratectonic Caledonides).

The main phase of Caledonian granite plutonism in Ireland when all the Newer granites of Leinster, Connemara, and Donegal were emplaced was about 405 ± 10 Ma*. Donegal granites which represent a single magmatic episode were emplaced by a range of intrusion mechanisms into metamorphosed, highly deformed Dalradian metasediments (Pitcher and Berger, 1972). The Thorr and Trawenagh Bay plutons were emplaced by piecemeal stoping, the aureole of the former showing early deformation accompanying stoping. Intrusion of the Rosses and Barnesmore complexes was 'permitted' (Pitcher, 1953; Walker and Leedal, 1954) with minimal metamorphic aureoles. Intense

* Calculated using $\lambda^{87}Rb = 1.42 \times 10^{-11}\ yr^{-1}$.

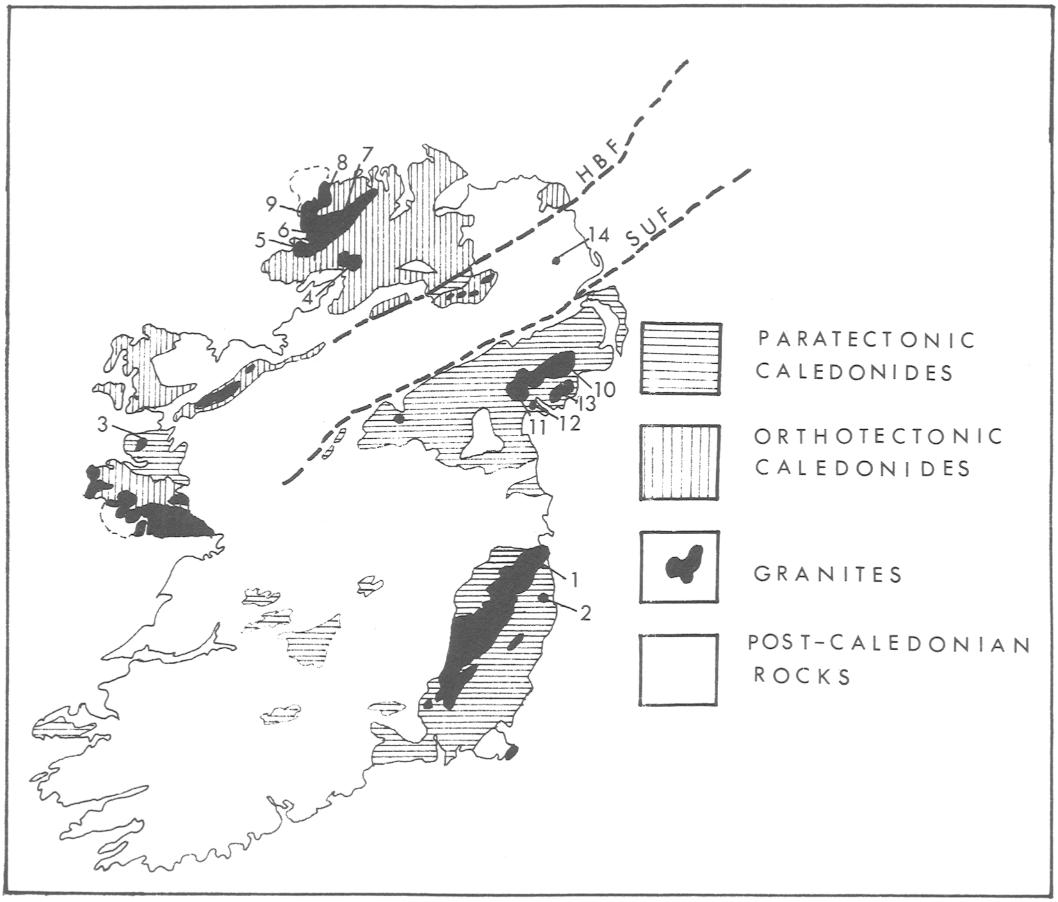

FIG. 1. Irish Granites: numbered plutons referred to in text and Table I are Caledonian Newer granites: (1) Leinster, (2) Carrigmore, (3) Corvock, (4) Barnesmore, (5) Ardara, (6) Trawenagh Bay, (7) Main Donegal, (8) Thorr, (9) Rosses, (10) Newry, and Tertiary granites: (11) Slieve Gullion, (12) Carlingford, (13) Mourne, (14) Tardree. SUF refers to the Southern Uplands Fault and HBF to the Highland Boundary Fault.

deformation, with the production of high-grade contact schists of regional aspect, accompanied emplacement of the Main Donegal (Pitcher and Read, 1959, 1960) and Ardara plutons (Akaad, 1956; Holder, 1979). Field evidence suggests that the probable sequence of emplacement was Thorr, Ardara, Rosses, Main Granite and Trawenagh Bay plutons; the isolated Barnesmore pluton (fig. 1) is difficult to place in the sequence.

The Leinster granite, with an outcrop area greater than 1500 km^2, is a major feature of the Paratectonic Caledonides of southeastern Ireland. The granite is composite and comprises five domed diapiric units arranged along a north-northeast axis (Brindley, 1973; Brück, 1974; Brück and O'Connor, 1977). Strong deformation accompanied intrusion and the aureole consists of andalusite-staurolite schists. The small Carrigmore diorite (4.2 km^2) lies to the east of the Leinster granite (fig. 1) and is of similar age (see Table III).

The Newry granodiorite comprises three domed units emplaced in the Lower Palaeozoic greywacke-slates of northeast Ireland; the aureole comprises static biotite-cordierite hornfels (Reynolds, 1944). The Corvock granite (Stanton, 1960; Inamdar and Kelly, 1979), in western Ireland, is a small (25 km^2) permitted pluton with a static biotite-hornfels aureole. The Galway granite complex (600 km^2) is composite and comprises several separate intrusive domes (Max *et al.*, 1978); andalusite-hornfels is developed.

Radioelement contents are given here for the Irish Newer granites of Leinster, Carrigmore, Corvock, Barnesmore, Ardara, Trawenagh Bay, the Main Donegal intrusion, Thorr, Rosses, and Newry. Data are not yet available for such older plutons as Carnsore, Oughterard, the Ox Mountains, and Saltees, while only sparse published radioelement data are available for the Newer Galway batholith (Lawrence, 1975).

Tertiary plutons. Ring complexes of Tertiary age were emplaced in northeastern Ireland and are represented by the Slieve Gullion, Carlingford, and Mourne centres (Richey, 1932). Each of these plutons represents a small batch of highly fractionated acid magma (Patterson, 1953; Meighan and Gamble, 1972), perhaps containing a substantial crustal melt component (O'Connor, 1976), emplaced at a high (subvolcanic) crustal level in ring fractures. Gravity and magnetic evidence (Cook and Murphy, 1952; Bullerwell, 1961, 1972) suggests that each of the centres is underlain by a large basic-ultrabasic mass. Both the Mourne and Carlingford centres are emplaced in Lower Palaeozoic metasediments of the Longford-Down massif, but the Slieve Gullion centre was emplaced in the Newer Caledonian Newry granodiorite.

The Carlingford complex (Le Bas, 1960) comprises gabbro and granophyre, with subordinate dolerite, basalt, and hybrid rock. The main granophyre (Le Bas, 1967) outcrops over an area of 30 km^2 in the central complex and may represent a ring dyke.

The Slieve Gullion complex (Emeleus, 1962) comprises an outer ring of porphyritic felsites and granophyres and a central complex of alternating dolerite and granophyre sheets (Reynolds, 1951; Bailey and McCallien, 1956). The Mourne granites (Emeleus, 1955) comprise two granite central complexes in which a series of five leucogranite types are developed.

The Tertiary complexes of northeastern Ireland and northwestern Scotland probably formed in a region of high geothermal gradient associated with sea-floor spreading in the north Atlantic and may represent a small aborted spreading centre. Whole-rock samples of granophyre and leucogranite mainly from Slieve Gullion and some samples from Carlingford, Mourne, and Tardree have been analysed for U, Th, and K.

Sampling and analytical methods

Rock samples, each weighing in excess of 5 kg, were collected from quarries, railway, and road cuttings. The freshest material available was selected and care was taken to collect suites of samples which reflected the lithological variations in the plutons, particularly in the case of the large Leinster and Main Donegal intrusions. Total gamma scintillometry was used to ensure that samples were not collected from radiometrically anomalous or mineralized sample sites.* The samples were jaw crushed and further ground in an agate Tema mill to obtain powders of less than 100 mesh size.

U and Th were determined by epithermal neutron activation analysis (Hennessy, 1979) at the Liverpool and Manchester Universities Research Reactor, Risley (U.K.). Potassium was determined by a combination of flame photometry (Leinster, Ardara, Rosses, and Newry samples), X-ray fluorescence (Corvock and Carrigmore samples) and instrumental neutron activation analysis (all other samples).

Radioelement abundances

The U, Th, and K contents in ten Irish Newer Caledonian plutons and four Irish Tertiary plutons are presented in Table I and fig. 2. Data for British Newer Caledonian granites are also presented (Hennessy, 1979 and pers. comm.). The values from Tammemagi and Smith (1975) and Tammemagi (1976) were determined by gamma spectrometry.

A more rigorous comparison of the various granite suites of Table I was made using the Mann-Whitney statistical test, which has been applied to the radioelement data of each pair of granite suites compared. The test is designed to detect differences in central tendency between any two distributions (Mann and Whitney, 1947; Siegel, 1956). The pairs for which significant differences exist in U, Th, and K contents or in the Th/U ratio are summarized in Table II.

Uranium. Among Irish Newer Caledonian plutons the Main Donegal granite has the lowest average content (2.5 ppm) and the Barnesmore granite the highest content (8.1 ppm) of U. Ninety-four Irish samples have a mean U content of 3.6 ppm while a mean of 4.3 ppm has been calculated from 194 British samples by Hennessy (1979). The Mann-Whitney test shows that the distribution of U differ significantly between British and Irish granites (Table II). Total gamma scintillometer data for the Galway granites (O'Connor, 1981) indicate that they are the most radioactive Newer Caledonian plutons in Ireland and U contents (T. McKillen, pers. comm.) suggest whole-rock levels in the range 5-15 ppm. Inclusion of such data would shift the mean for Irish Caledonian granites closer to that for the British Caledonian intrusions.

The mean for all granites (228 samples) of the British Isles Caledonian Province is 4.0 ppm U,

* Mineralogical examination indicated late-stage hydrothermal alteration of samples from Leinster and Donegal.

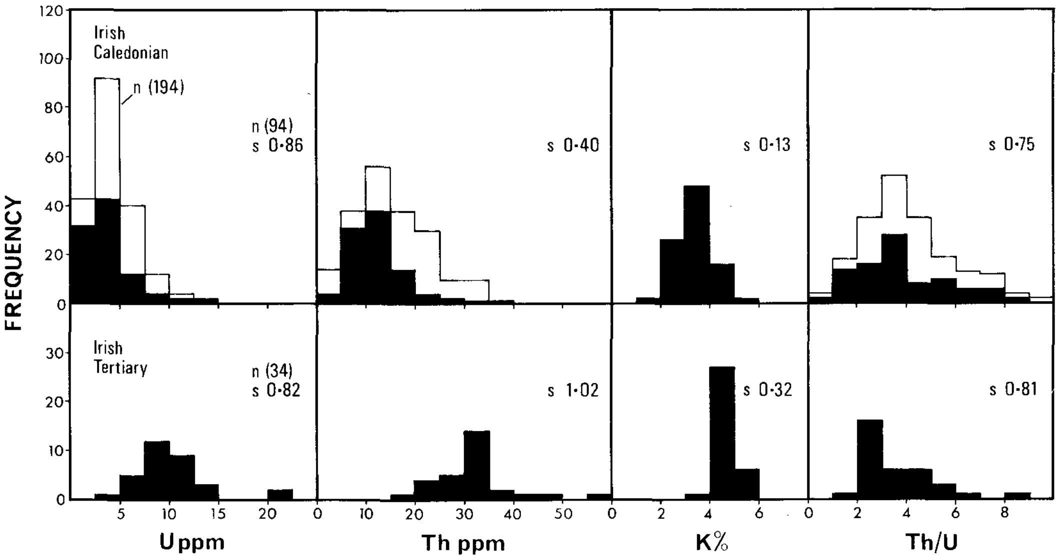

FIG. 2. Sample frequency histograms of U, Th, K, Th/U in Caledonian and Tertiary granites from Britain and Ireland (data from this paper; Hennessy, 1979; Tammemagi and Smith, 1975). n = 194 refers to British Caledonian granites (Hennessy, 1979); 's' is Pearson's second coefficient of skewness.

TABLE I. *Comparative mean radioelement abundances for Irish and British granites**

Rock suite†	No. of samples	U (ppm)	Th (ppm)	K %	Th/U	Reference
Irish						
Caledonian plutons						
1. Leinster pluton	13	3.1(1.3)	7.7(2.4)	3.49(0.25)	2.76(1.13)	O'Connor *et al.* (1981*a*)
2. Carrigmore pluton	9	3.6(2.3)	7.6(3.5)	2.86(0.87)	2.41(1.17)	O'Connor *et al.* (1981*d*)
3. Corvock pluton	7	3.7(1.7)	14.8(4.7)	3.04(0.54)	4.38(1.76)	O'Connor *et al.* (1981*b*)
4. Barnesmore pluton	3	8.1(1.9)	25.1(2.3)	4.13(0.84)	3.16(0.50)	O'Connor *et al.* (1981*b*)
5. Ardara pluton	9	4.4(1.8)	13.2(6.0)	3.05(0.36)	3.19(1.13)	O'Connor *et al.* (1981*b*)
6. Trawenagh Bay pluton	4	5.0(1.1)	10.1(4.9)	3.78(0.76)	1.98(0.66)	O'Connor *et al.* (1981*b*)
7. Main Donegal pluton	27	2.5(1.5)	12.9(5.1)	3.62(0.82)	5.84(2.29)	O'Connor *et al.* (1981*b*)
8. Thorr pluton	12	3.1(1.4)	13.0(3.4)	3.46(0.64)	4.80(2.23)	O'Connor *et al.* (1981*b*)
9. Rosses pluton	4	5.6(4.9)	10.6(2.3)	3.90(0.07)	3.75(3.34)	O'Connor *et al.* (1981*b*)
10. Newry pluton	6	4.5(1.3)	13.2(2.8)	2.90(0.31)	3.29(1.46)	O'Connor *et al.* (1981*b*)
Irish Caledonian	94	3.6(2.1)	12.1(5.3)	3.40(0.70)	4.09(2.23)	This paper
British Caledonian	*194*	*4.3(2.4)*	*15.1(7.6)*	—	3.95(1.85)	Hennessy (1979)
All Caledonian	288	4.0(2.3)	14.1(7.1)	—	4.00(1.98)	This paper and Hennessy (1979)
British Hercynian	36	11.4(4.4)	19.6(4.8)	4.35(0.45)	2.12(1.28)	Tammemagi and Smith (1975)
Irish						
Tertiary plutons						
11. Slieve Gullion granophyres	25	10.0(2.5)	30.3(5.2)	4.51(0.32)	3.21(0.95)	O'Connor, in prep.
12. Carlingford granophyres	4	8.5(1.6)	50.9(10.6)	5.01(0.29)	6.19(1.81)	O'Connor, in prep.
13. Mourne granites	4	27.9(10.1)	91.1(16.5)	4.10(0.18)	3.48(1.01)	O'Connor, in prep.
14. Tardree rhyolite	1	5.5	30.9	4.39	5.62	O'Connor, in prep.
Irish Tertiary	34	11.8(7.1)	39.9(21.4)	4.52(0.37)	3.66(1.45)	This paper

* All U, Th data determined by epithermal neutron activation analysis, except data of Tammemagi and Smith (1975) which were determined by gamma spectrometry: numbers in brackets are 1 sigma.

† Number refers to fig. 1.

TABLE II. *Results of Mann–Whitney tests (corrected for ties)* on primary radioelement data of various distribution pairs from Table I*

Distribution comparison†	U	Th	K	Th/U
Irish Caledonian (94)–British Caledonian (194)	0.002	0.001	—	0
Irish Caledonian (94)–Irish Tertiary (34)	0.001	0.001	0.001	0
All Caledonian (288)–Irish Tertiary (34)	0.001	0.001	—	0

* Values tabulated represent the level of significance (α) at which the null hypothesis (H_0) is rejected for a one-tailed test; zero signifies that H_0 is accepted. (H_0 = no difference in central tendency of the two distributions compared.)
† Numbers in brackets refer to sample numbers.

which is the clarke of uranium for granites (Rogers and Adams, 1969). Similar values have been reported by Simpson *et al.* (1976, 1979) for British Newer Caledonian granites.

Among Irish Tertiary plutons the Mourne granites show the highest U contents (mean 27.9 ppm) and the Tardree rhyolite the lowest values (5.5 ppm); the Slieve Gullion and Carlingford granophyres have intermediate contents. The mean U for thirty-four Irish Tertiary samples is 11.8 ppm which is significantly higher than the Caledonian mean (Table II) and the clarke for granite. However, other acid rocks from the Tertiary Province (e.g. Skye epigranites) have low U contents in the range 1–2 ppm (Moorbath and Welke, 1969; Tammemagi, 1976). Mann–Whitney tests (not reported here) indicate that statistically significant between-pluton differences exist for most of the Tertiary centres investigated. Distribution of U in Irish Caledonian and Tertiary granites are positively skewed (fig. 2), the latter showing a much greater dispersion of U whole-rock values.

Thorium. Among Irish Newer Caledonian granites the Leinster pluton has the lowest Th content (7.7 ppm); the highest contents are in the Barnesmore pluton (25.1 ppm). The over-all Irish mean of 12.1 ppm for the Irish Caledonian granites is significantly less than the British mean of 15.1 ppm (Table II) and the mean for all British Isles Caledonian granites of 14.1 ppm is slightly lower than the average for granites of 18 ppm (Rogers and Adams, 1969). Data for Th in the Galway granites suggest levels in the range 20–60 ppm (Lawrence, 1975; T. McKillen pers. comm.) and inclusion of these data would bring the Irish and British means into closer agreement.

Irish Tertiary rocks have high Th levels, with twice the clarke value for granite; they are significantly higher than Caledonian granites (Table II). However, Tammemagi (1976) reports low Th levels of 5–10 ppm for Skye epigranites. Caledonian and Tertiary Th distributions are positively skewed (fig. 2). Tertiary plutons show the greatest dispersion of Th values; and five samples, mainly from the Mournes, have Th values greater than 60 ppm. The Tertiary Th distribution is multi-modal and Mann–Whitney tests indicate that significant between-pluton differences exist.

Potassium. Among Irish Caledonian plutons granodiorites are reflected by their low K contents (e.g. Newry 2.9 %) and the more leucocratic by higher values (e.g. Barnesmore 4.1 %). The Irish Caledonian mean of 3.4 % K is similar to the clarke of 3.6 % K for granites (Rogers and Adams, 1969). K abundance data were not available for British Caledonian samples, although the mean is probably similar to that of the Irish Caledonian intrusions and the clarke for granite. K levels in Irish Tertiary granites are significantly higher (mean 4.52 %) than Caledonian granites and the Tertiary K distribution is slightly positively skewed (fig. 2).

Th/U ratios. Irish Caledonian Th/U ratios vary from 1.98 (Trawenagh Bay) to 5.84 (Main Donegal) with a mean of 4.09 which is not significantly different (Table II) from the British Caledonian mean of 3.95; a combined Caledonian mean of 4.00 is similar to that for average granites (Rogers and Adams, 1969). The mean Th/U ratio for Irish Tertiary rocks is 3.66. Both the Caledonian and Tertiary Th/U distributions are strongly positively skewed (fig. 2).

Radioelement distribution and variation

Such large-ion lithophile (LIL) elements as U, Th, and K tend to accumulate in the late stage members of igneous differentiation series (Rogers and Adams, 1969). The degree of fractionation of such melts is often indicated by indices based on major element or trace element data. Such data are available for most of the Irish samples studied here (except the Trawenagh Bay and Barnesmore samples), and U, Th, and K have been plotted against the Differentiation Index (Thornton and Tuttle, 1960) in order to determine trends in individual plutons.

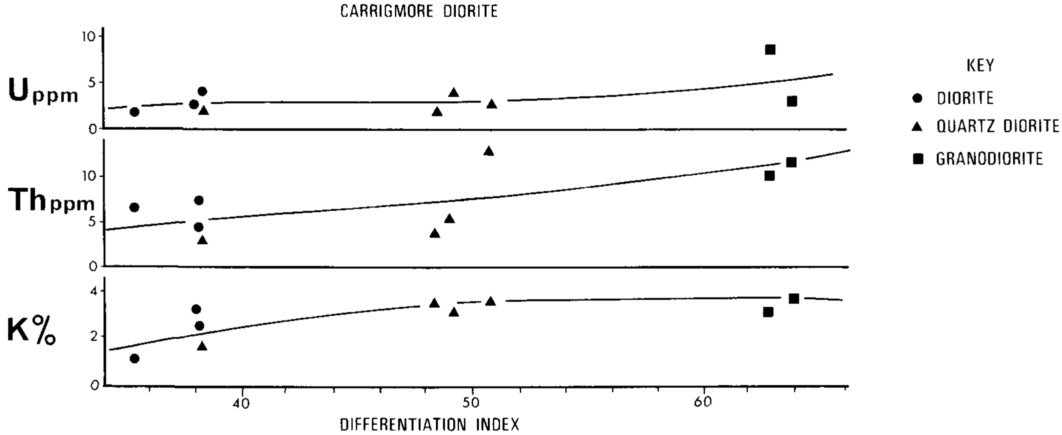

FIG. 3. Variation of U, Th, and K with the Differentiation Index in the Carrigmore diorite, Co. Wicklow (O'Connor *et al.*, 1981*d*).

Uranium. Among Caledonian plutons only the Carrigmore diorite shows U enrichment (fig. 3) from diorite to granodiorite (O'Connor *et al.*, 1981*d*). In this pluton U correlates with levels of several major and trace elements and fission-track studies (T. Williams, pers. comm.) show that it occurs in primary resistate phases such as sphene, zircon, and apatite. In the larger Irish plutons the compositional range is often much more restricted and clear fractionation trends are less apparent.

In the Leinster granite, U correlates with alkali elements at the 0.05 level of significance (O'Connor *et al.*, 1981*a*) and it is suggested that extensive late-stage hydrothermal alteration (Brück and O'Connor, 1977) redistributed U in the host rock. Fission-track studies show that, while up to 40% of the whole-rock U is in resistate mineral phases, most U is in late-stage minerals associated with chloritization and sericitization and at grain boundaries; a hematite-magnetite phase associated with mica breakdown contains in excess of 500 ppm U.

Limited trace element data are available for samples from the Donegal granites (Main Granite, Thorr, Ardara, Rosses). U is positively correlated with Rb and negatively with Sr and K/Rb in these rock suites (fig. 4). Autoradiography and fission-track studies of the Main Donegal granite (O'Connor and Long, unpublished data) show that U occurs in resistate minerals (zircon, apatite, sphene) and as discrete uraninite grains associated with biotite, particularly in certain pegmatitic zones.

Tertiary samples have a restricted compositional range (70-7% SiO_2). U levels tend to remain constant with fractionation (fig. 5) of the Slieve Gullion and Carlingford granophyres; residual aplites in the Mournes have reduced levels of U (possibly because of the absence of a volatile phase). Fission-track data for these samples are not yet

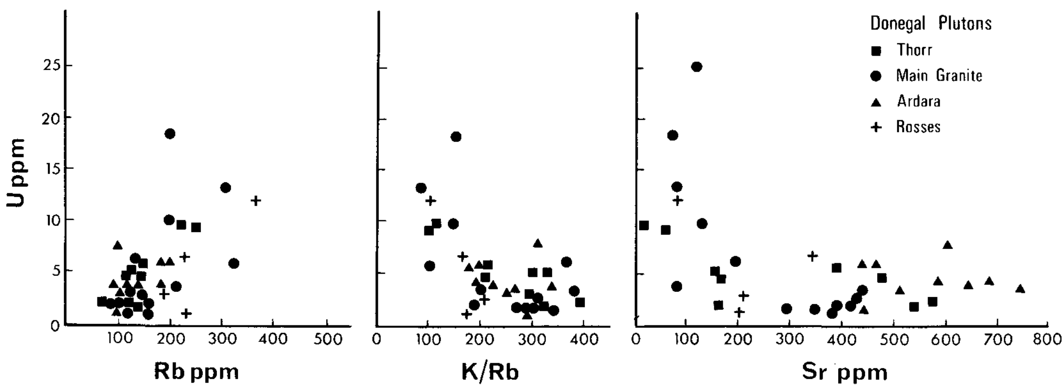

FIG. 4. Correlation of U with Rb, Sr and K/Rb in some Donegal plutons.

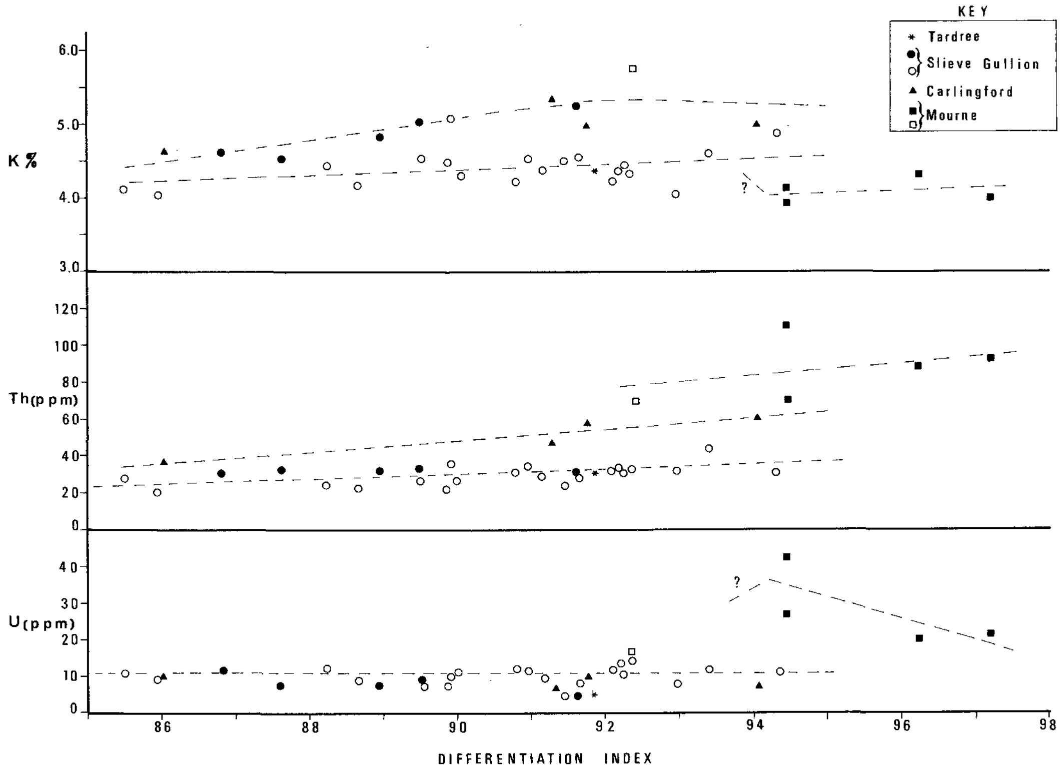

FIG. 5. Variation of U, Th, and K with Differentiation Index in Tertiary acid rocks, northeast Ireland.

available. However, primary apatite (with minor zircon, monazite, etc.) occurs in Tertiary acid rocks; most of the U probably occurs in such phases. The high U levels in the Mourne granites suggest that a discrete U phase may be present.

Thorium. In the Carrigmore diorite (fig. 3) and the outer monzodiorite of the Ardara pluton Th

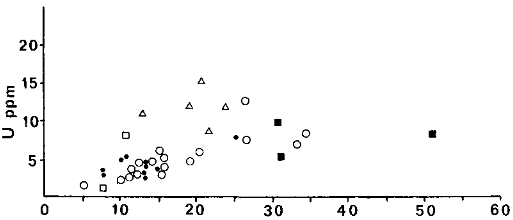

FIG. 6. Variation of U and Th for British and Irish granites. Closed circle = Irish Caledonian granites (data in Table I); open circle = British Caledonian granites (data from Hennessy, 1979 and Plant *et al.*, 1980); closed square = Irish Tertiary granites (data in Table I; Mourne samples not shown); open square = Lundy and Skye (data from Tammemagi, 1976); open triangle = British Hercynian granites (data from Tammemagi and Smith, 1975).

increases with increasing SiO_2. Th correlates with major and trace elements in most of the plutons and is strongly correlated with Zr in the Leinster, Ardara, and other plutons (O'Connor *et al.*, 1981*b*) suggesting that it occurs in accessory minerals. In all the Tertiary suites studied Th levels increase with increasing fractionation; the trends for each complex are well defined on variation diagrams with no overlap (fig. 5).

Potassium. In most Irish Tertiary and Caledonian plutons K increases with fractionation although in some suites (Leinster, Ardara, and Newry) K remains more or less constant with increasing fractionation. The mean U–Th compositions of Irish and British granites are shown in fig. 6. The fields of Irish and British Caledonian granites overlap and both suites show a positive correlation between U and Th (see also Plant *et al.*, 1980). The Tertiary overlaps the Caledonian suite but shows a greater range of values (the Mourne samples cannot be represented on this diagram). Some British Hercynian plutons (Lands End, Dartmoor, Bodmin, St. Austell, and Carnmenellis) are included for comparison (Tammemagi and Smith, 1975); they plot in a separate field.

Uranium mineralization

The Irish Newer Caledonian plutons of Galway, Barnesmore, and Rosses are enriched in LIL elements (Lawrence, 1975; Hall, 1967). The latest and most fractionated magma in the Galway granite is a fine-grained leucogranite, with U levels in the range 5–15 ppm, and high Th levels (T. McKillen, pers. comm.). The Barnesmore pluton (Co. Donegal) also has high U and Th levels (Table I). Fission-track data are not available but it is likely that the radioelements in both the Barnesmore and Galway plutons occur in resistate phases. In the Rosses pluton, Burke *et al.* (1964) report the occurrence of rare torbernite (with pyrite along a joint plane) and uraninite (in a heavy mineral concentrate) in association with the main greisen lens at the Sheskinarone beryl locality. While each of these plutons has relatively high whole-rock contents of U and Th, they are *not* associated with significant U mineralization.

In contrast, the voluminous Leinster and Donegal plutons are associated with important U mineralization. The principal uranium anomaly of the Leinster granite occurs in peat over the Tullow Lowlands unit some 5 km from the nearest intrusive contact, suggesting that U mineralization occurs in the pluton. The source of the U has not been located despite intensive exploration but blocks of lepidolite greisen with joint coatings of uraniferous microlite (Steiger, 1977) have been found near the eastern contact of this unit of the Leinster granite. The Leinster granite has a strong Li-Sn-Be-F-U association (Brück and O'Connor, 1977) and has been affected by extensive hydrothermal alteration phenomena (muscovitization, sericitization, tourmalinization, hematization, albitization, chloritization and carbonatization) which is often most intense along major transverse fracture zones in the batholith (Brück and O'Connor, 1980); vein-type base metal (principally Pb and Zn) mineralization is associated with the transverse fracture system and may be Caledonian in age (Brück and O'Connor, 1980) rather than Hercynian (Moorbath, 1962).

The Main Donegal granite (450 km^2) has mainly concordant contacts, a compositional banding, a strong mineral alignment, a preferred orientation of inclusions and a synkinematic schist envelope (Pitcher and Berger, 1972). Composition varies from biotite granodiorite to granite proper. The pluton has extensive and complex sheeted contact zones with abundant pegmatites and microgranite sheets, together with numerous raft trains of varied Dalradian lithologies. A revised 9-point whole-rock Rb-Sr isochron age of 407 ± 4 Ma has recently been obtained (Table III) by O'Connor *et al.* (1981*c*). Fission-track studies (O'Connor and Long, unpublished data) show that U occurs in resistate phases (e.g. zircon, apatite, sphene) and as discrete uraninite grains mainly associated with biotite in pegmatites in the raft zones and marginal areas of the pluton. $^{207}Pb/^{206}Pb$ ages of 406–7 Ma have been determined on uraninite, concordant with the age of emplacement of the Main Granite (O'Connor and Long, unpublished data). Similar age relations have been described for uraninites in southwestern England and in Portuguese Hercynian plutons (Basham *et al.*, 1979).

Discussion

The granite suites of Britain and Ireland represent acid magmas generated in different thermal and tectonic regimes. Caledonian plutons may represent subduction-related granites formed on the margins of a proto-Atlantic ocean, later members of the suite (the Newer granites) being emplaced following closure and displaying a wide range of intrusive styles. Tertiary plutons are

TABLE III. *Rb-Sr whole-rock ages and initial* $^{87}Sr/^{86}Sr$ *ratios of selected Irish Newer Caledonian granites*

	Pluton	Age (Ma)	Initial ratio	Reference
Forceful	Thorr	413 ± 3	0.70555 ± 7	O'Connor *et al.*, 1981*c*
	Ardara	405 ± 5	0.70665 ± 6	Halliday *et al.*, 1980
	Main Donegal	407 ± 4	0.7065 ± 1	O'Connor *et al.*, 1981*c*
	Leinster	404 ± 4	0.7078 ± 4	O'Connor and Brück, 1978
	Carrigmore	409 ± 10	0.7055 ± 1	O'Connor and Reeves, 1979
	Newry	393 ± 21	0.7059 ± 2	O'Connor, 1975
Permitted	Trawenagh Bay	405 ± 3	0.7052 ± 4	Halliday *et al.*, 1980
	Rosses	404 ± 3	0.7062 ± 2	Halliday *et al.*, 1980

$\lambda^{87}Rb = 1.42 \times 10^{-11}\ yr^{-1}$. Errors on ages and initial Sr isotope ratios are two sigma and are of York's *a priori* type (York, 1969).

related to crustal rifting in the north Atlantic. The extent to which the radioelement chemistry of the granites reflects their source composition and which, if any, process of granite production (and, hence, geodynamic setting) is most favourable for U deposition and concentration is considered. The application of total uranium contents to discriminate between mineralized and barren granites (cf. Simpson *et al.*, 1976, 1979) is also discussed, although it should be noted that these authors always used fission-track studies to interpret the significance of whole-rock uranium values.

Classification of Irish Newer Caledonian granites. Read (1961) established a structural/temporal classification of Scottish Newer granites in which these plutons could be broadly subdivided into earlier 'forceful' and later 'permitted' intrusions. However, as the earliest member of the Donegal granite suite (Thorr) was 'permitted' and the latest member (Main Granite) was 'forceful' the *temporal* aspect of Read's classification does not apply.

Nevertheless, Read's *structural* subdivision of granites into forcefully emplaced and permitted intrusions can still be applied to Irish Newer Caledonian granites (Brindley, 1969; Pitcher and Berger, 1972; Leake, 1978). Read considered the Main Donegal, Ardara, Newry, and Leinster granites to be forceful intrusions and the Rosses and Barnesmore centres as permitted. Extending his scheme to other granites, the various plutons of the Galway batholith (Max *et al.*, 1978; Leake, 1978) and the Corvock granite (Stanton, 1960; Inamdar and Kelly, 1979), all of which have static hornfels aureoles, are permitted intrusions.

Other classifications have been developed for British Newer granites based on geophysical, geochemical, and/or isotopic parameters (Brown and Locke, 1979; Plant *et al.*, 1980; Pankhurst *et al.*, 1981). It was found difficult to apply these schemes simply to Irish Newer granites mostly because the temporal aspects of Read's structural classification do not apply. They are therefore classified using Read's structural/field criteria.

Isotopic evidence of granite magma source. Irish Newer Caledonian granites have initial $^{87}Sr/^{86}Sr$ ratios in the range 0.704–0.710 (O'Connor, 1974, and Table III) with no clear age or isotopic distinction between forceful and permitted plutons (Table III) and Pankhurst (1979) also noted that there was no distinction between the initial Sr isotope ratios of forceful and permitted intrusions for British Newer granites, although forceful Newer granites show a greater dispersion of initial Sr isotope ratios than the permitted group. Low initial ratios in the range 0.704–0.708, are typical of I-type granites (Chappel and White, 1974) often generated at destructive plate margins and may indicate a mantle/lower crustal source region for these late Caledonian magmas (Brown and O'Connor, 1978). However, magmas with low initial Sr isotope ratios can form by melting young igneous rocks, immature sediments (greywacke) or old crustal rocks with low Rb/Sr ratios (Faure and Powell, 1972; Harmon and Halliday, 1980).

Older and early forceful granites of Scotland with ratios > 0.710 (Pankhurst, 1979) contain inherited zircons presumed to be derived by partial or complete melting of older crustal rocks (Pidgeon and Aftalion, 1978). Inherited zircons also occur in forceful Newer granites north of the Highland Boundary Fault (e.g. Foyers, Helmsdale, Thorr) in both Scotland and Ireland, whereas the Newer granites investigated south of this fault generally lack an inherited zircon component, as do the permitted Newer granites *regardless* of their location in the orogen. This led Pidgeon and Aftalion (1978) to conclude that Caledonian acid magmas in the Southern Uplands and Lake District were derived by partial melting of middle Palaeozoic source rocks, while those to the north in Scotland were derived from Proterozoic sources. Halliday *et al.* (1979) pointed out that Moine and Lower Palaeozoic sediments contain inherited zircons which could be incorporated at a high crustal level by assimilation rather than being present at the magma source although this might be reflected by higher initial Sr isotope ratios. Simpson *et al.* (1979) proposed a predominantly juvenile source for some late permitted intrusions in Scotland while Pankhurst (1979) proposed a common origin for both forceful and permitted magmas by melting of an isotopically juvenile basic crust at high pressures. The presence of an inherited zircon component, preserving ages of 1000–2000 Ma, supports a crustal component however (whether by melting or assimilation) in the forceful Caledonian granites, north of the Highland Boundary Fault in Scotland and Ireland.

Irish Tertiary granites have high initial Sr isotope ratios of 0.710 or more, comparable with their Scottish counterparts (O'Connor, 1976, and unpublished data). It has been suggested that the acid magmas were produced either (i) by partial melting of upper crustal rocks in contact with these subjacent masses of basic magma (e.g. Moorbath and Bell, 1965) or (ii) differentiation of the basic magmas (Beckinsale, 1974). In view of the large volumes of basic magma involved, some partial melting of crustal rocks is likely to have occurred and Sr and Pb isotopic data (Moorbath and Welke, 1968; Taylor and Forester, 1971) indicate contamination with crustal material, either by mixing with partially-melted crustal rocks or by equilibration with crustal Sr and Pb in hydrothermal convection systems. The wide range of radioelement distributions supports the concept of an important crustal contribution to the acid magmas. Moreover, Tertiary plutons emplaced in old Lewisian basement (e.g. Skye), depleted in U, Th, and other incompatible elements, tend to have low radioelement abundances whereas those emplaced in Lower Palaeozoic sediments (e.g. Mourne) have high radioelement contents. These primary differences between Tertiary centres have been further enhanced by fractionation.

Granite suites and metallogenesis. The permitted Irish Newer Caledonian granites (Galway, Barnesmore, Rosses) contain high levels of radioelements but are not associated with U mineralization. A similar situation has been noted by Plant *et al.* (1980) in relation to the 'discordant' metalliferous Cairngorm granite of Scotland.

In contrast, the voluminous Irish Newer forceful granites such as the Leinster and Main Donegal intrusions have low whole-rock U and Th levels but are associated with significant U mineralization. The precise nature of the U mineralization in the Leinster granite is unknown but that associated with pegmatites in the Main Donegal pluton occurred at a high temperature contemporaneously with consolidation of the intrusion. The source of the U mineralization associated with the Main Donegal pluton is obscure however. Whole-rock U levels (1–5 ppm) of fresh unmineralized samples preclude the production, by magmatic fractionation, of a uraninite-rich pegmatitic granite in restricted linear zones within the intrusion. The linear zones may represent healed early shear zones (W. S. Pitcher, pers. comm.); emplacement of the Main Granite within a major NE–SW shear belt has been demonstrated by Hutton (1981). The shear zones appear to have acted as pathways for the ascent of U-bearing solutions from considerable depth which interacted with the pluton during its final stages of consolidation.

Thus whole-rock U levels of Irish Caledonian intrusions cannot be used as a criterion of potential mineralization. Moreover the concept of 'fertile' granite containing large quantities of leachable uranium, as suggested by Moreau (1977), should perhaps be restricted to the European Hercynian province.

Conclusions

A study of data for U, Th, and K in Irish Newer Caledonian and Tertiary plutons indicates that

(i) Many Newer Caledonian granites have radioelement abundances similar to the clarke for granite, suggesting that the magmas were derived from a widespread and fairly uniform source such as the lower crust or upper mantle, an origin supported by isotopic evidence. Irish forceful plutons (Leinster, Main Donegal) tend to have lower than average whole-rock radioelement contents, whereas Irish permitted plutons (Barnesmore, Rosses, Galway) have higher radioelement levels.

(ii) U mineralization is associated with Irish forceful plutons but not with permitted plutons; parallels exist among the Newer Scottish granites e.g. Helmsdale versus Cairngorm (see Plant *et al.*, 1980).

(iii) Unlike Hercynian granites, whole-rock U contents are not a good guide to potential U mineralization among Newer Caledonian granites in Ireland.

(iv) U mineralization in the forceful Main Donegal granite was contemporaneous with emplacement and is largely pegmatite-hosted. Linear mineralized pegmatitic zones may represent healed early shears which acted as pathways for the ascent of U-bearing solutions.

(v) Irish Tertiary plutons have high radioelement contents but no significant U mineralization, suggesting that extreme magmatic fractionation of small volumes of acid magma (e.g. Mournes) does not produce economic concentrations of U. Isotopic evidence suggests that crustal materials are involved in the genesis of the acid melts and radioelement abundances appear to support this: plutons emplaced in depleted basement (e.g. Skye) have low radioelement contents whereas those emplaced in younger cover sediments (Mourne) have high radioelement contents. Thus individual Tertiary plutons may reflect their source composition to a greater extent than might be expected for such evolved magmas.

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REFERENCES

Akaad, M. K. (1956). *J. geol. Soc. London*, **112**, 263–88.

Bailey, E. B. and McCallien, W. J. (1956). *Liverpool Manchester geol. J.* **1**, 466–501.

Basham, I. R., Vairinho, M. M. B., and Bowles, J. F. W. (1979). Paper Tc-295-1, *Geology of vein and similar type uranium deposits*, I.A.E.A. (Lisbon).

Beckinsale, R. D. (1974). *Earth Planet. Sci. Lett.* **22**, 267–74.

Bowie, S. H. U., Simpson, P. R., and Rice, C. M. (1973). *In* Jones, M. J. (ed.), *Geochemical Exploration*, Inst. Mining Metall. 359–72.

Brindley, J. C. (1969). *In* Kay, M. (ed.), *North Atlantic—geology and continental drift*, Mem. 12 Am. Assoc. Pet. geol., 336-53.
——(1973). *Sci. Proc. R. Dublin Soc.* **5A,** 27-36.
Brown, G. C. and Locke, C. A. (1979). *Earth Planet. Sci. Lett.* **45,** 69-79.
——and O'Connor, P. J. (1978). *Geophys. J.R. astron. Soc.* **53,** 177.
Brück, P. M. (1974). *Bull. geol. Surv. Ireland,* **1,** 381-93.
——and O'Connor, P. J. (1977). Ibid. **2,** 107-41.
————(1980). Ibid. **2,** 349-70.
Bullerwell, W. (1961). *Irish Nat. J.* **13,** 255-7.
——(1972). *Phil. Trans. R. Soc. London,* **271A,** 209-15.
Burke, K. C., Cunningham, M. A., Gallagher, M. J., and Hawkes, J. R. (1964). *Econ. Geol.* **59,** 1539-50.
Chappel, B. W. and White, A. J. R. (1974). *Pacific Geol.* **8,** 173-74.
Cook, A. H. and Murphy, T. (1952). *Geophys. Mem. Dubl. Inst. Adv. Studies,* **2** (4), 27 pp.
Emeleus, C. H. (1955). *Sci. Proc. R. Dublin Soc.* **27,** 35-50.
——(1962). *Proc. R. Irish Acad.* **62B,** 55-76.
Faure, G. and Powell, J. L. (1972). *Strontium Isotope Geology,* Springer-Verlag (New York).
Hall, A. (1967). *Geol. Mag.* **104,** 99-109.
Halliday, A. N., Aftalion, M., van Breemen, O., and Jocelyn, J. (1979). *In* Harris, A. L., Holland, C. H., and Leake, B. E. (eds.), *The Caledonides of the British Isles—reviewed.* Spec. Pub. No. 8 Geol. Soc. London, 653-61.
————and Leake, B. E. (1980). *Nature, London,* **284,** 542-3.
Harmon, R. S. and Halliday, A. N. (1980). Ibid. **283,** 21-5.
Hennessy, J. (1979). Ph.D. thesis. University of Liverpool.
Holder, M. T. (1979). *In* Atherton, M. P. and Tarney, J. (eds.), *Origin of granite batholiths: geochemical evidence,* Shiva Publishing, 116-28.
Hutton, D. (1981). *J. Struct. Geol.* **3,** 93.
Inamdar, D. D. and Kelly, T. J. (1979). *Bull. geol. Surv. Ireland,* **2,** 333-48.
Lawrence, G. (1975). *In* Elliott, I. L. and Fletcher, W. K. (eds.), *Geochemical exploration 1974,* 353-70 (Elsevier).
Le Bas, M. J. (1960). *Trans. R. Soc. Edinburgh,* **64,** 169-200.
——(1967). *Proc. R. Irish Acad.* **65B,** 325-38.
Leake, B. E. (1978). *In* Bowes, D. R. and Leake, B. E. (eds.), *Geol. J. Spec. Issue No. 10,* 221-48.
Mann, H. B. and Whitney, D. R. (1947). *Ann. Math. Statist.* **18,** 50-60.
Max, M. D., Long, C. B., and Geoghegan, M. A. (1978). *Bull. geol. Surv. Ireland,* **2,** 223-33.
Meighan, I. G. and Gamble, J. A. (1972). *Nature Phys. Sci.* **240,** 183-4.
Moorbath, S. (1962). *Phil. Trans. R. Soc. London,* **254A,** 295-360.
——and Bell, J. D. (1965). *J. Petrol.* **6,** 37-66.
——and Welke, H. (1968). *Earth planet. Sci. Lett.* **1,** 113-17.
————(1969). Ibid. **5,** 217-30.
Moreau, M. (1977). *In* Jones, M. J. (ed.), *Geology, mining and extractive processing of uranium,* Inst. Mining Metall. 83-102.
O'Connor, P. J. (1974). *Bull. geol. Surv. Ireland,* **1,** 471-5.
——(1975). *Sci. Proc. R. Dublin Soc.* **5A,** 407-13.
——(1976). *Geol. Mag.* **113,** 389-91.
——(1981). *Geol. Surv. Ireland Rep. Series RS 81/1* (Geophysics) 26 pp.
——and Brück, P. M. (1978). *J. Earth Sci. R. Dublin Soc.* **1,** 105-13.
——and Reeves, T. J. (1979). *Bull. geol. Surv. Ireland,* **2,** 307-14.
——Hennessy, J., Brück, P. M., and Williams, C. T. (1981*a*). *Geol. Mag.* (in press).
——Long, C. B., and Hennessy, J. (1981*b*). *Bull. geol. Surv. Ireland* (in press).
————Kennan, P. S., Halliday, A. N., and Max, M. D. (1981*c*). Uppsala Caledonide meeting (in press).
——Reeves, T. J., and Hennessy, J. (1981*d*). *Bull. geol. Surv. Ireland,* **3,** 9-16.
Pankhurst, R. J. (1979). *In* Atherton, M. P. and Tarney, J. (eds.), *Origin of granite batholiths: geochemical evidence,* Shiva Publishing, 34-44.
——Sutherland, D. S., Brown, G. C., and Pitcher, W. S. (1981). *In* Sutherland, D. S. (ed.), *Igneous Rocks of the British Isles,* John Wiley and Sons Ltd., 149-190.
Patterson, E. M. (1953). *Proc. R. Irish Acad.* **55B,** 171-88.
Pidgeon, R. T. and Aftalion, M. (1978). *Geol. J. Spec. Issue,* No. 10, 183-220.
Pitcher, W. S. (1953). *J. geol. Soc. London,* **108,** 413-41.
——and Berger, A. R. (1972). *The Geology of Donegal,* Wiley-Interscience.
——and Read, H. H. (1959). *J. geol. Soc. London,* **114,** 259-300.
————(1960). Ibid. **116,** 1-36.
Plant, J., Brown, G. C., Simpson, P. R., and Smith, R. T. (1980). *Trans. Inst. Mining Metall.* **89B,** 198-210.
Read, H. H. (1961). *Liverpool Manchester geol. J.* **2,** 653-83.
Reynolds, D. L. (1944). *J. geol. Soc. London,* **99,** 205-40.
——(1951). *Trans. R. Soc. Edinburgh,* **62,** 85-143.
Richey, J. E. (1932). *Trans. geol. Soc. Glasgow,* **19,** 42-140.
Rogers, J. J. W. and Adams, J. A. S. (1969). *In* Wedepohl, K. H. (ed.), *Handbook of Geochemistry,* Springer-Verlag, **2,** 92.
Siegel, S. (1956). *Nonparametric statistics for the behavioural sciences,* McGraw-Hill.
Simpson, P. R., Plant, J., and Cope, M. J. (1976). *In* Jones, M. J. (ed.), *Geology, mining and extractive processing of uranium,* Inst. Mining Metall. 126-39.
——Brown, G. C., Plant, J., and Ostle, D. (1979). *Phil. Trans. R. Soc. London,* **291**A, 385-412.
Stanton, W. I. (1960). *J. geol. Soc. London,* **116,** 269-90.
Steiger, R. (1977). In *Prospecting in areas of glaciated terrain,* Instn. Mining Metall. 14-24.
Tammemagi, H. Y. (1976). *Geol. Mag.* **113,** 271-6.
——and Smith, M. L. (1975). *J. geol. Soc. London,* **131,** 415-27.
Taylor, H. P. and Forester, R. W. (1971). *J. Petrol.* **12,** 465-97.
Thirlaway, H. I. S. (1951). *Geophys. Mem. Dubl. Inst. Adv. Studies,* **2** (2), 26 pp.
Thornton, C. P. and Tuttle, O. F. (1960). *Am. J. Sci.* **258,** 664-84.
Walker, G. P. L. and Leedal, G. P. (1954). *Sci. Proc. R. Dublin Soc.* **26,** 207-43.
York, D. (1969). *Earth Planet. Sci. Lett.* **5,** 320-4.
Young, D. G. G. (1974). *Proc. R. Irish Acad.* **74**B, 63-73.

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