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Long-lived granite-related molybdenite mineralization at Connemara, western Irish Caledonides

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Abstract – New Re–Os age determinations from the Galway Granite (samples: KMG = 402.2 ± 1.1 Ma, LLG = 399.5 ± 1.7 Ma and GBM = 383.3 ± 1.1 Ma) show that in south Connemara, late Caledonian granite-related molybdenite mineralization extended from *c.* 423 Ma to *c.* 380 Ma. These events overlap and are in excellent agreement with the published granite emplacement history determined by U–Pb zircon geochronology. The spatial distribution of the late-Caledonian Connemara granites indicates that initial emplacement and molybdenite mineralization occurred at *c.* 420 Ma (that is, the Omey Granite and probably the Inish, Leterfrack and Roundstone granites) to the N and NW of the Skird Rocks Fault, an extension of the orogen-parallel Southern Uplands Fault in western Ireland. A generally southern and eastward progression of granite emplacement (and molybdenite mineralization) sited along the Skird Rocks Fault then followed, at *c.* 410 Ma (Roundstone Murvey and Carna granites), at *c.* 400 Ma (Errisbeg Townland Granite, Megacrystic Granite, Mingling Mixing Zone Granodiorite, Lough Lurgan Granite and Kilkieran Murvey Granite) and at *c.* 380 Ma (Costelloe Murvey Granite, Shannapheasteen and Knock granites). The duration of granite magmatism and mineralization in Connemara is similar to other sectors of the Appalachian–Caledonian orogeny and several tectonic processes (e.g. slab-breakoff, asthenospheric flow, transtension and decompression) may account for the duration and variety of granite magmatism of the western Irish Caledonides.

Keywords: molybdenite, granite, Connemara, Caledonides, Re–Os chronometry.

1. Introduction

The late-Caledonian granites of south Connemara occupy a key location in the western Irish Caledonides. The granites comprise the Galway Granite and its satellite plutons Roundstone, Inish, Omey and Letterfrack (Fig. 1). The Galway Granite's 80 km long, WNW-trending axis reflects a stitching relationship between the granite and the EW-trending Skird Rocks Fault. This fault is a splay of the orogen-parallel Southern Uplands Fault and one of a number of major strike-slip faults that parallel the Iapetus suture in the British and Irish Caledonides (Leake, 1978; Dewey & Strachan, 2003). The Skird Rocks Fault separates high-grade metamorphic rocks of the Connemara Massif from Lower Ordovician greenschist-facies metavolcanic and metasedimentary rocks (Fig. 1). Recent U–Pb zircon and Re–Os molybdenite geochronology from the Galway Granite provide constraints on the timing of final motion on the orogen-parallel strike-slip Southern Uplands–Skird Rocks Fault System to *c.* 410 Ma, in keeping with time constraints for final movement on the Great Glen Fault (Feely *et al.* 2003; Selby, Creaser & Feely, 2004). Furthermore, Re–Os molybdenite age determinations from the Omey Granite showed that granite emplacement and molybdenite mineralization occurred at *c.* 422 Ma, pre-dating the emplacement of the main Galway Granite by *c.* 10 Ma (Feely *et al.* 2007). Within this framework, however, the age of granite-related molybdenite mineralization only extends from *c.* 422 to *c.* 408 Ma. We present new Re–Os molybdenite ages from three new localities in the central sector of the main Galway Granite which demonstrate that the time span for molybdenite mineralization in Connemara must be significantly extended (*c.* 20 Ma), reflecting long-lived granite emplacement and granite-related molybdenite mineralization in Connemara.

2. The Galway Granite

The late-Caledonian calc-alkaline Galway Granite was emplaced between *c.* 410 Ma and 380 Ma (Feely *et al.* 2003; Selby, Creaser & Feely, 2004) into the 474.5 to 462.5 Ma Metagabbro–Gneiss Suite to the north (Leake, 1989; Leake & Tanner, 1994; Friedrich *et al.* 1999), and into Lower Ordovician greenschist-facies rocks (South Connemara Group) to the south (McKie & Burke, 1955; Williams, Armstrong & Harper, 1988; see Fig. 1). Gravity and aeromagnetic maps indicate that the Granite extends for several kilometres beneath the Carboniferous rocks of the Galway Bay area (Murphy, 1952; Max, Ryan & Inamdar, 1983). Two major faults, the NNE-trending Shannawona Fault and the NW-trending Barna Fault, divide the Granite into

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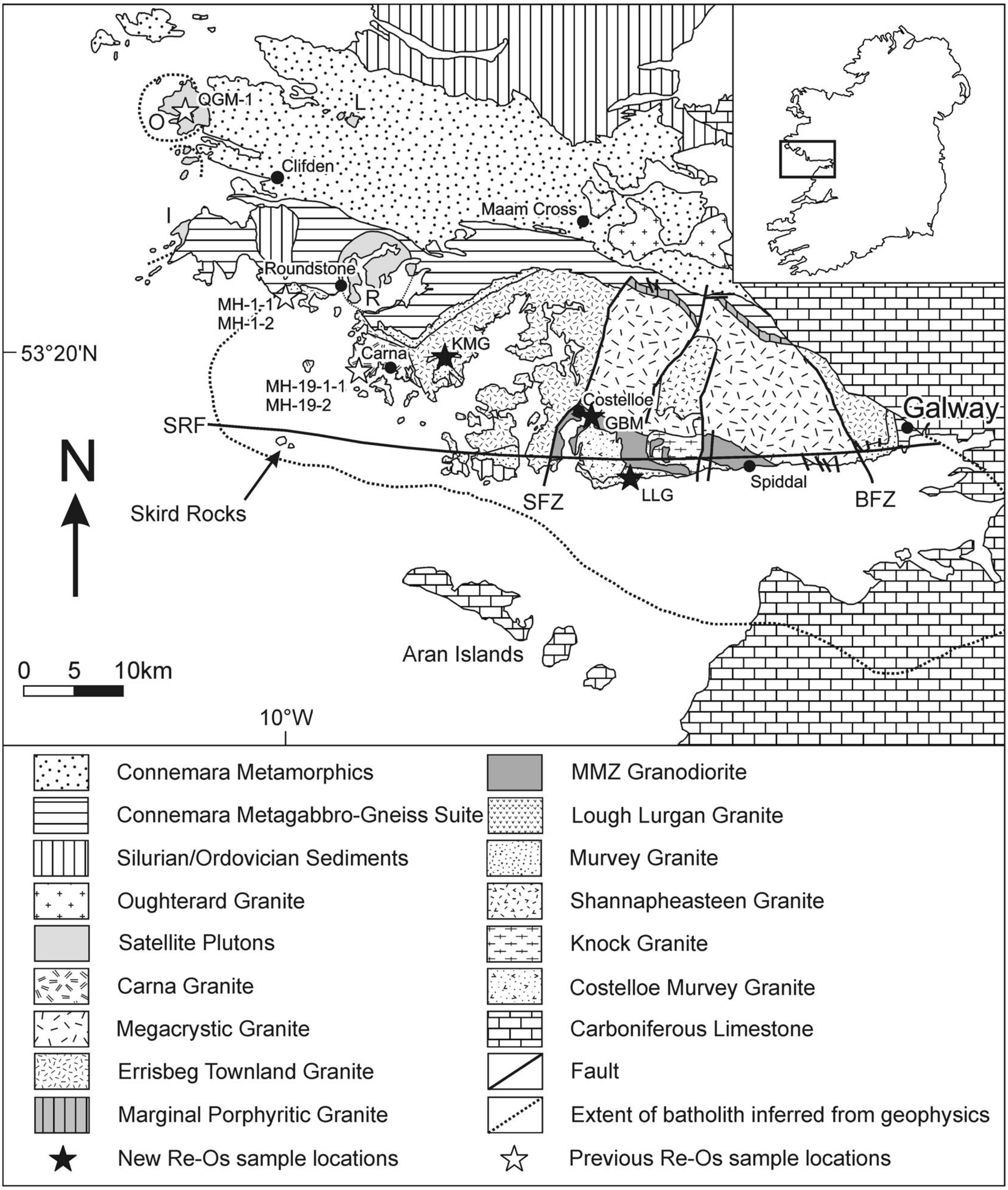

Figure 1. Geological map of Galway Bay area. The Galway Granite's main varieties are shown: Carna, Errisbeg Townland, Megacrystic, Mingling Mixing Zone (MMZ) and Lough Lurgan and Murvey (including Roundstone and Kilkieran varieties) Granites are the earliest, followed by the Shannapheasteen, Knock and Costelloe Murvey granites. Satellite plutons are Letterfrack (L), Omey (O), Inish (I) and Roundstone (R) granites. The older (463 Ma: Friedrich *et al.* 1999) Oughterard Granite of east Connemara is also shown. Geology adapted from Townend (1966), Leake & Tanner (1994), Pracht *et al.* (2004), Feely *et al.* (2006) and Leake (2006). SFZ – Shannowona Fault Zone; BFZ – Barna Fault Zone; SRF – Skird Rocks Fault.

three blocks: the western, central and eastern blocks (Fig. 1).

The western block comprises lithologies that range from granodiorite (Carna Granite) through granite (Errisbeg Townland Granite) to an alkali leucogranite (Murvey Granite). The two latter types also occur in the eastern block (Coats & Wilson, 1971).

The central block (the area between the Shannawona Fault and Barna Fault) exposes a significantly broader spectrum of lithologies ranging from quartz diorites through granodiorites and granites to alkali granite. A zone of magma mingling and mixing (MMZ) active during emplacement of the Galway Granite is bounded to the north by a concordant contact with the foliated Megacrystic Granite and intruded to the south by the transgressive Lough Lurgan Granite (El-Desouky, Feely & Mohr, 1996).

The petrology, geochemistry and field relationships of the central block granites has been described in detail by the following: El-Desouky, Feely & Mohr (1996), Crowley & Feely (1997), Baxter *et al.* (2005), Feely *et al.* (2006) and Leake (2006). These studies present unequivocal evidence for several phases of granite emplacement. Intergranite relationships indicate that the Megacrystic Granite was emplaced first along with the MMZ Granodiorite and its enclaves of coeval diorite magma. These fabrics within the Megacrystic Granite and MMZ Granodiorite are suggested to relate to successive emplacement of magma batches (e.g. Megacrystic Granite and MMZ Granodiorite and Lough Lurgan Granite: Baxter *et al.* 2005). In addition, detailed mapping of the central and northern parts this block suggest that emplacement was incremental by progressive northward marginal dyke injection and stoping of the country rocks (Leake, 2006). These granites were intruded by the Shannapheasteen, Knock and Costelloe Murvey granites (Crowley & Feely, 1997; Feely *et al.* 2006; Leake, 2006).

3. Granite-related molybdenite mineralization, south Connemara

Disseminated and quartz vein-hosted molybdenite mineralization occurs throughout the late-Caledonian Galway Granite and its satellite plutons (O'Raghallaigh *et al.* 1997). Notable occurrences are at the western end of the Galway Granite, that is, at Mace Head and Murvey (Derham, 1986; Derham & Feely, 1988; Max & Talbot, 1986; Gallagher *et al.* 1992; Fig. 1). Molybdenite-bearing quartz veins (∼ 5–30 cm thick) at Mace Head trend NE–SW, their orientation controlled by early jointing in the host granite (Derham, 1986; Max & Talbot, 1986). Vein minerals also include chalcopyrite, pyrite, magnetite and muscovite. The Roundstone Murvey Granite contains both fine-grained (∼ 5 mm) disseminated and quartz vein hosted molybdenite. There is an estimated 240 000 t at 0.13 % Mo in this low-grade deposit (Max & Talbot, 1986). In the Omey granite, disseminated molybdenite (2–4 mm) and rosettes (∼ 5 mm across) are hosted by thin, discontinuous quartz veins (< 5 cm across) that trend NE–SW across the central sector of the pluton (Feely *et al.* 2007). The quartz veins typically contain muscovite-bearing alteration selvages similar to that encountered in Carna Granite (at Mace Head) and Roundstone Murvey Granite molybdenite deposits (Gallagher *et al.* 1992).

Geochemical, fluid inclusion and stable isotope (O, H, S and C) studies indicate that the molybdenite mineralization in the Carna Granite (at Mace Head) and Roundstone Murvey Granite was magmatic in origin (Gallagher *et al.* 1992). O'Reilly *et al.* (1997) concluded that a H_2O–CO_2–NaCl-bearing fluid of moderate salinity (4–10 eq. wt % NaCl) deposited late-magmatic molybdenite mineralized quartz veins. This fluid composition is similar to molybdenite-bearing vein quartz in the Omey Granite (Feely *et al.* 2007).

Thermal Ionization Mass Spectrometry (TIMS)-based U–Pb zircon geochronology of the Galway Granite indicates that emplacement occurred over a period of at least 20 Ma from *c.* 400 to 380 Ma (Feely *et al.* 2003). Molybdenite Re–Os ages for granite-related molybdenite mineralization (Omey Granite, Roundstone Murvey Granite and Carna Granite from Mace Head; Fig. 1) at the western end of the batholith extend the period of magmatic activity by *c.* 20 Ma from 423 to 380 Ma (Selby, Creaser & Feely, 2004; Feely *et al.* 2007). This geochronology indicates granite emplacement spanned a period of *c.* 40 Ma. We present below three new Re–Os molybdenite ages that indicate a similar time span for molybdenite mineralization in south Connemara.

4. Sampling and analytical methods

Molybdenite Re–Os geochronology was carried out on aliquants of mineral separates of disseminated molybdenite from the Kilkieran Murvey Granite (sample KMG), the Lough Lurgan Granite (sample LLG) and quartz vein hosted molybdenite from the MMZ Granodiorite (sample GBM; Fig. 1). These samples were collected following the results of Re–Os molybdenite geochronology of the Omey Granite, which showed that the initiation of granite magma emplacement in south Connemara was much earlier (*c.* 12 Ma) than previously thought (Feely *et al.* 2007). The geology of the three samples analysed for Re–Os geochronology is described below.

Sample KMG. Disseminated molybdenite and chalcopyrite mineralization occurs in the Kilkieran Murvey Granite, which is similar to the Roundstone Murvey Granite (Wright, 1964). Mineralization extends over an area of about four square kilometres to the NW of the village of Kilkieran. The leucocratic granite has a grainsize of < 5 mm and contains quartz (∼ 35 %), K-feldspar (∼ 35 %), plagioclase (∼ 25 %) and biotite (∼ 5 %). The disseminated flakes of molybdenite are generally < 2 mm. The sample was collected in a disused roadside quarry between the water treatment station and Kilkieran village (GR L835,322).

Sample GBM. The molybdenite mineralization occurs along a prominent road-cutting 0.5 km S of Costelloe village (GR L968,274). Sample GBM is from a NE striking vertical 2 cm thick quartz vein within the road section containing abundant molybdenite and chalcopyrite (< 3 mm grain size). The quartz vein can be traced along strike for ∼ 5 m and cross-cuts the coarse grained (5–10 mm) MMZ Granodiorite.

Sample LLG. Fine disseminations of molybdenite (< 2 mm) occur in the Lough Lurgan Granite 200 m

Table 1. Re and Os abundances and model ages for molybdenite, late Caledonian Connemara granites, Ireland

Sample no.	Sample wt (mg)	Total Re (ppm)	^{187}Re (ppm)	^{187}Os (ppb)	Re–Os age (Ma)
Omey[1]					
QGM-1	22	150.46 ± 0.55	94.57 ± 0.35	667.9 ± 2.1	422.5 ± 1.7
Murvey[2]					
MH-1-1	103	5.14 ± 0.01	3.23 ± 0.01	22.16 ± 0.04	410.5 ± 1.5
MH-1-2	103	5.09 ± 0.01	3.20 ± 0.01	21.97 ± 0.04	410.8 ± 1.4
Mace Head[2]					
MH-19-1-1	11	75.74 ± 0.36	47.60 ± 0.23	325.0 ± 0.9	407.3 ± 1.5
MH-19-2	20	75.92 ± 0.27	47.72 ± 0.17	325.0 ± 0.9	407.3 ± 1.5
Kilkieran[3]					
KMG	30	54.11 ± 0.14	34.01 ± 0.08	228.7 ± 0.4	402.2 ± 1.1
Costelloe[3]					
GBM	99	3.16 ± 0.01	1.99 ± 0.01	12.73 ± 0.02	383.3 ± 1.1
Inveran[3]					
LLG	413	0.531 ± 0.001	0.334 ± 0.001	2.230 ± 0.003	399.5 ± 1.7

Data sources: [1]Feely *et al.* (2007); [2]Selby *et al.* (2004); [3]this study

SW of the contact with the Costelloe Murvey Granite (GR M008, 216). The host Lough Lurgan Granite is a greyish pink granite of 1 to 7 mm grainsize (El Desouky, Feely & Mohr, 1996).

The molybdenite samples were analysed for their Re and ^{187}Os abundances by Isotope Dilution Negative Thermal Ionization Mass Spectrometry (ID-NTIMS) at the Northern Centre for Isotopic and Elemental Tracing facility at Durham University. Detailed sample preparation and analytical protocols are given by Selby & Creaser (2001), Selby & Creaser (2004) and Selby *et al.* (2007). In brief, molybdenite was isolated from the host rock or quartz vein using traditional mineral separation techniques (crushing, Frantz magnetic separation, heavy liquids (MI and LST), and water flotation). An aliquant of the molybdenite separate was digested in a 3:1 mix of HNO_3:HCl (inverse *aqua regia*) with an known amount of mixed isotope tracer (^{185}Re and normal Os) in a carius tube at 220 °C for 24 hours. Osmium was purified from the acid mix using solvent extraction ($CHCl_3$) and micro-distillation methods. Rhenium was purified using anion column chromatography. The purified Os and Re were loaded to Pt and Ni filaments, respectively. The isotope ratios were measured using NTIMS on a Thermo Electron TRITON thermal ionization mass spectrometer using Faraday collectors. Although insignificant to the Re and Os abundance in the three molybdenite samples analysed in this study, all Re and Os data were blank corrected. All three molybdenite samples were analysed at the same time. The full procedural blank during for Re and Os is 2 picograms (pg) and 0.5 pg, respectively, with an ^{187}Os/^{188}Os blank composition of 0.17 ± 0.02 (n = 1). The determined Re and ^{187}Os abundances together with the ^{187}Re decay constant (1.666×10^{-11} a^{-1}; Smoliar, Walker & Morgan, 1996) are used to calculate Re–Os molybdenite model dates. As a check on analytical accuracy and reproducibility, an in-house and inter-laboratory ‘control’ Chinese molybdenite powder was also analysed during the period of this study (HLP-5; Stein, Markey & Morgan, 1997). This molybdenite control sample yields an average Re–Os age of 219.9 ± 0.7 Ma (0.32 % 2σ, n = 3). This age is within the uncertainty reported by Markey, Stein & Morgan (1998; 221.0 ± 2 Ma, 0.8 % 2σ, n = 19) and Selby & Creaser (2004; 220.5 ± 0.2, 0.11 % 2σ, n = 17).

5. Results

The Re–Os molybdenite data, with uncertainties at the 2σ level, for the three samples are reported in Table 1. This table also presents the previously reported Re–Os molybdenite data for samples from Omey Granite, Roundstone Murvey Granite and Carna Granite (Selby, Creaser & Feely, 2004; Feely *et al.* 2007). Molybdenite from the six granite samples shows significant differences in Re and ^{187}Os abundance (Table 1). The lowest Re and ^{187}Os abundances occur in samples LLG (Re = 0.531 ± 0.001 ppm and ^{187}Os = 2.230 ± 0.003 ppb) and GBM (Re = 3.16 ± 0.01 ppm and ^{187}Os = 12.73 ± 0.02 ppb). Relatively low abundances also occur in the Roundstone Murvey Granite sample (MH-1-1 Re = 5.14± 0.01 ppm and ^{187}Os = 22.16 ± 0.04 ppb). The Omey granite sample QGM-1 contains the highest abundance of Re (150.46 ± 0.55 ppm) and ^{187}Os (667.9 ± 2.1 ppb). The samples from the Carna Granite (MH-19–1-1) and Kilkieran Murvey Granite (KMG) are also relatively enriched in Re (∼ 76 and 54 ppm) and ^{187}Os (∼ 325, 229), respectively. The ^{187}Re and ^{187}Os molybdenite data for the samples investigated in this study (KMG, GBM, LLG) yield Re–Os model dates of 402.2 ± 1.1, 383.3 ± 1.1 and 399.5 ± 1.7 Ma, respectively (Table 1). Table 2 and Figure 2 present all the Re–Os molybdenite and U–Pb zircon dates for the Connemara region. Figure 2 highlights the close agreement between the zircon and molybdenite dates across the region.

6. Discussion

The new and existing Re–Os isotopic data for the south Connemara granites show that episodic granite-related molybdenite mineralization extended over a period of

Table 2. Tabulation of age determinations presented in the text

Granite/samples	Method	Age
KMG Kilkieran Murvey Granite disseminated molybdenite	Re–Os molydenite	402.2 ± 1.1 Ma[6]
Megacrystic Granite	U–Pb single crystal (zircon)	394.4 ± 2.2 Ma[1]
Megacrystic Granite	U–Pb single crystal (zircon)	*c.* 402 Ma[1]
Enclave in MMZ Granodiorite	U–Pb single crystal (zircon)	397.7 ± 1.1 Ma[1]
MMZ Granodiorite	U–Pb single crystal (zircon)	399.5 ± 0.8 Ma[1]
GBM MMZ Granodiorite molybdenite in quartz vein	Re–Os molybdenite	383.3 ± 1.1 Ma[6]
Costelloe Murvey Granite	U–Pb single crystal (zircon)	380.1 ± 5.5 Ma[1]
LLG Lough Lurgan Granite disseminated molybdenite	Re–Os molybdenite	399.5 ±1.7 Ma[6]
MH-19-1-1; MH-19-2 Carna Granite (Mace Head) molybdenite in quartz vein	Re–Os molybdenite	407.3 ± 1.5 Ma[2]
MH-1-1 Roundstone Murvey Granite disseminated molybdenite	Re–Os molybdenite	410.5 ± 1.5 Ma[2]
MH-1-2 Roundstone Murvey Granite disseminated molybdenite	Re–Os molybdenite	410.8 ± 1.4 Ma[2]
Carna Granite	U–Pb bulk zircon	412 ± 15 Ma[3]
QGM-1 Omey Granite molybdenite in quartz vein	Re–Os molybdenite	422.5 ± 1.7 Ma[5]
Omey Granite	U–Pb single crystal (zircon)	*c.* 420 Ma[4]

Sources: [1]Feely *et al.* (2003); [2]Selby *et al.* (2004); [3]Pidgeon (1969); [4]Buchwaldt *et al.* (2001); [5]Feely *et al.* (2007); [6]this study.

c. 40 Ma, that is, from *c.* 423 Ma in the NW Omey pluton to *c.* 383 Ma at Costelloe in the east. While the Re–Os age determinations for sample KMG and LLG are consistent with predictions from field relationships, sample GBM yields the youngest Re–Os age so far determined for the Galway Granite. The quartz vein cuts the MMZ Granodiorite, which is *c.* 400 Ma based upon TIMS single zircon U–Pb age determinations (Feely *et al.* 2003). The gap of *c.* 17 Ma between granite zircon crystallization and deposition of molybdenite can be explained by relating the mineralization to the final stages of magmatic activity in the Galway Granite, in particular the *c.* 380 Ma Costelloe Murvey Granite (Feely *et al.* 2003), which is located < 1 km to the south of the sample location.

Buchwaldt *et al.* (1998, 2001) reported U–Pb and Pb–Pb zircon ages (single grain evaporation) that yielded a *c.* 420 Ma age for the Omey Granite and a *c.* 400 to 380 Ma range for emplacement of the Galway Granite. More recent U–Pb zircon age determinations for the Galway Granite, using TIMS (Feely *et al.* 2003), support the findings of Buchwaldt *et al.* (1998, 2001). However, Re–Os age determinations for molybdenite at the western end of the Galway Granite yield ages from *c.* 410 Ma at Murvey, to *c.* 407 Ma at Mace Head. A bulk zircon age determination (Pidgeon, 1969) for the Carna Granite, which hosts the molybdenite at Mace Head, yielded an age of 412 ± 15 Ma. Combining (a) the three new molybdenite ages reported here with those of Selby, Creaser & Feely (2004) and Feely *et al.* (2007) and (b) the zircon ages of Pidgeon, (1969), Buchwaldt *et al.* (1998, 2001) and Feely *et al.* (2003) shows that Connemara granite emplacement and related molybdenite mineralization extended from *c.* 423 Ma to 380 Ma.

The spatial distribution of the U–Pb and Re–Os ages indicates that the emplacement of individual plutons and the deposition of granite-related molybdenite

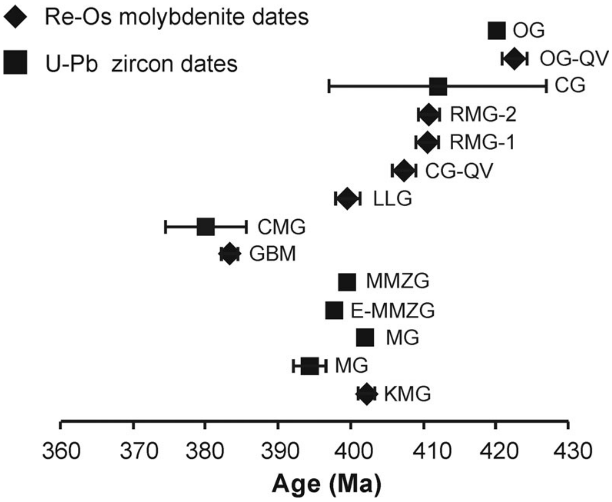

Figure 2. Comparative plot of Re–Os molybdenite and U–Pb zircon data for the Connemara Granites using data in Table 2. KMG – Kilkieran Murvey Granite; MG – Megacrystic Granite; E-MMZG – enclave in MMZ Granodiorite; MMZG – MMZ Granodiorite; GBM – Molybdenite-bearing quartz vein in MMZ Granodiorite; CMG – Costelloe Murvey Granite; LLG – Lough Lurgan Granite; CGQV – Molybdenite-bearing quartz vein in Carna Granite; RMG-1 and RMG-2 – Roundstone Murvey Granite; CG – Carna Granite; OG-QV – Molybdenite-bearing quartz vein in Omey Granite; OG – Omey Granite.

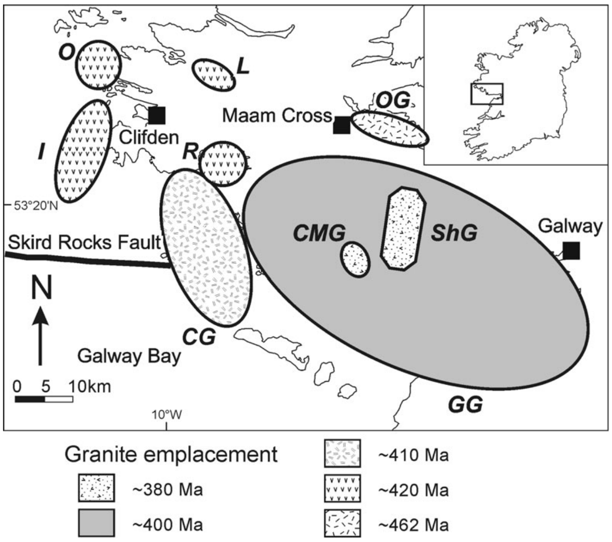

Figure 3. Schematic diagram showing the spatial and temporal distribution of Connemara's late-Caledonian granites. O – Omey Granite; L – Letterfrack Granite; I – Inish Granite; R – Roundstone Granite; CG – Carna Granite + Roundstone Murvey Granite; GG – Main Galway Granite (Megacrystic Granite, Errisbeg Townland Granite, MMZ Granodiorite, Lough Lurgan Granite and Kilkieran Murvey Granite); ShG – Shannapheasteen Granite and CMG – Costelloe Murvey Granite. OG is the Oughterard Granite.

commenced in the NW of Connemara with the Omey Granite probably accompanied by the other satellite plutons, that is, the Inish, Letterfrack and Roundstone plutons. The granite-related molybdenite Re–Os ages for the western end of the Galway Granite gave a minimum age for Carna Granite emplacement of 407 Ma, post-dating the emplacement of the Roundstone Murvey Granite at 410 Ma, in keeping with field relationships mapped by Leake (1974). Further east, the U–Pb and Re–Os ages indicate granite emplacement and molybdenite mineralization took place at *c.* 400 Ma and *c.* 380 Ma (Fig. 3).

The prolonged and episodic emplacement of the south Connemara Granites, from *c.* 423 to 380 Ma, is similar to the span of emplacement ages recorded from other sectors of the Appalachian–Caledonian orogeny (Fig. 4). The emplacement of post-collisional granites is commonly associated with major crustal lineaments, such as the Skirds Rock Fault in south Connemara, and numerous authors have proposed a genetic relationship between tectonics and magmatism (Watson, 1984; Jacques & Reavy 1994; Neilson, Kokelaar & Crowley, 2009). However, it is unlikely that granite magmatism is related to a single tectonic event with a duration of *c.* 50 Ma, and a number of tectonic models have been proposed to account for the variety of granite magmatism observed across the Appalachian–Caledonian orogeny. In light of the geochronological data presented above, the granites of South Connemara can now be placed within this tectonic framework.

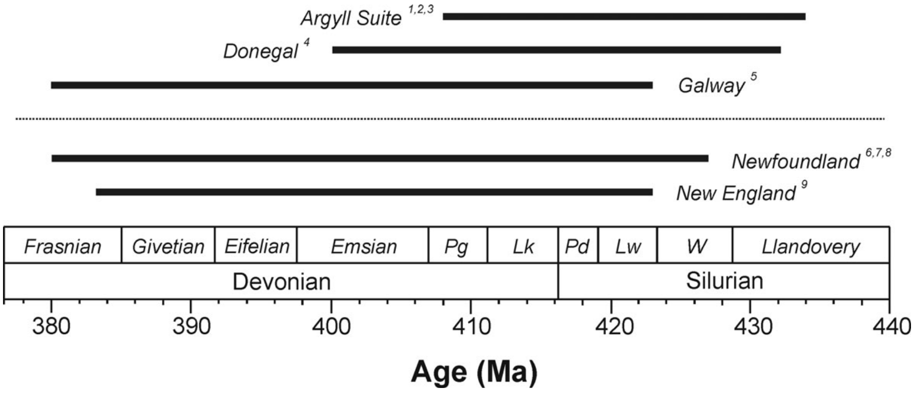

Figure 4. Range of emplacement ages for post-collisional granites in the Appalachian–Caledonian orogeny. 1 – Neilson, Kokelaar & Crowley (2009); 2 – Conliffe *et al.* (2010); 3 – Porter & Selby (2010); 4 – Condon *et al.* (2004); 5 – this study; 6 – Kerr (1997); 7 – Whalen *et al.* (2006); 8 – Lynch *et al.* (2009); 9 – Bradley *et al.* (2000).

Atherton & Ghani (2002) proposed a slab break-off model to account for the onset of ‘syn-collisional magmatism’ in the Scottish Highlands, whereby the detachment of the subducted Iapetus lithospheric slab followed the collision of Laurentia with Baltica, allowing the ascent of the ‘dry’ hot asthenospheric material which impacted against the lithospheric mantle. Similarly, Whalen *et al.* (2006) argued that the onset of granite magmatism in Newfoundland was related to slab break-off. Initial granite emplacement in south Connemara is broadly synchronous with other sectors of the Appalachian–Caledonian orogeny, for example, Donegal (*c.* 428 Ma; Condon *et al.* 2004), Argyll Suite (*c.* 434 Ma; Conliffe *et al.* 2010), Newfoundland (*c.* 432 Ma; Whalen *et al.* 2006); New England (*c.* 423 Ma; Bradley *et al.* 2000). This suggests that slab break-off may also be responsible for early granite magmatism in south Connemara, and was relatively synchronous across the Appalachian–Caledonian orogeny.

Neilson, Kokelaar & Crowley (2009) showed that asthenospheric flow, providing mantle-derived (appinite–lamprophyre) magmas in the Scottish Highlands, occurred for *c.* 22 Ma after slab break-off. These authors argued that heat and volatiles derived from this magma would be sufficient to generate the large volumes of intermediate-silicic magmas in the Argyll Suite Granites. Geochemical similarities between the main Galway Granites and the Argyll Suite Granites (Q. Crowley, unpub. Ph.D. thesis, Nat. Univ. Ireland, Galway, 1997) indicate a similar source of granite magmas, and therefore the emplacement of the main Galway Granite may be related to prolonged asthenospheric flow following slab break-off. The ascent of granite magma was facilitated by extensional fractures associated with a releasing bend on the sinistrally moving Skird Rocks Fault (Leake, 2006). The final stages of magmatic activity in the Galway Granite (e.g. emplacement of the Costelloe Murvey Granite) may be associated with Devonian transtension, decompression and heating of enriched Avalonian sub-continental lithosphere (Brown *et al.* 2008).

7. Conclusions

This study reports three new Re–Os molybdenite ages from the Galway Granite. When these ages are combined with published Re–Os molybdenite ages (Selby, Creaser & Feely, 2004 and Feely *et al.* 2007) and the zircon ages of Pidgeon (1969), Buchwaldt *et al.* (1998, 2001) and Feely *et al.* (2003), they show that Connemara granite emplacement and related molybdenite mineralization extended from *c.* 423 Ma to 380 Ma. The spatial and temporal distribution of the granites shows that initial emplacement (*c.* 420 Ma) occurred in the NW of Connemara with later granites (*c.* 410 to 380 Ma) sited to the south and east, along the extension of the Southern Uplands Fault (the Skird Rocks Fault) in western Ireland. The prolonged nature of magmatism in south Connemara is comparable to other sectors of the Appalachian–Caledonian orogeny, and a number of tectonic processes (e.g. slab-breakoff, asthenospheric flow, transtension and decompression) may account for the duration and variety of granite magmatism in south Connemara.

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