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ABSTRACT

Two new U-Pb geochronology dates from the Inish Granite (main granite: 423.21 ± 0.30 Ma; marginal granite 428 +17/-11 Ma) show that emplacement of the south Connemara Granites extended from approximately 430 Ma to 380 Ma. These ages are consistent with the recent model Re-Os age determinations for the Omey Granite (422.5 ± 1.7 Ma) and suggest that the Letterfrack and Roundstone granites were also emplaced around the same time. Field relations of the Inish Granite show relative age differences for the main and marginal granite, with quartz-feldspar porphyry dikes cross-cutting the marginal granite but not the main granite. These relations suggest that emplacement of the marginal granite occurred, followed by the quartz-feldspar porphyry dikes, and assembly of the Inish Granite culminated with intrusion of the main phase. The time span of emplacement of the calc-alkaline south Connemara Granites is similar to that of the mid-Paleozoic alkalic plutons located in southeastern New England, USA (426 Ma to 377 Ma), linking hypothesised intraplate rifting in West Avalonia and prolonged magmatism in Laurentia. This provides further support for the model of Avalonia subduction beneath Laurentia in the Siluro-Devonian time period, and suggests that the end of magmatic activity for both suites indicated the complete closure of the Iapetus Ocean.

INTRODUCTION

The Galway Granite is a late-Caledonian calc-alkaline batholith thought to have been assembled between about 410 and 380 Ma on the basis of U-Pb and Re-Os molybdenite ages (Figure 1; Feely et al., 2003). It has four plutons surrounding it (Roundstone, Inish, Omey and Letterfrack) that are commonly referred to as “satellite plutons” (Figure 1; Hunt, 2015). The Galway Granite and its satellite plutons are collectively known as the south Connemara Granites (Feely et al., 2003, Feely et al., 2010). Recent model Re-Os molybdenite ages from mineralized zones in the Omey Granite suggest magmatic activity around 423 Ma, therefore extending the assembly of the south Connemara Granites and molybdenite mineralization to 423-380 Ma (Feely et al., 2010). However, the 10 Ma gap between the age of Mo mineralization in the Galway Granite and Omey Granite raise concerns over accepting the model Re-Os as the true age of emplacement. Zircon U-Pb data from two samples of the Inish Granite, one from the main granite and one from the marginal granite are presented here in order to confirm the model Re-Os ages (Figure 1). These data provide a clearer picture of the time span of emplacement of the Galway Granite and its satellite plutons, and help elucidate the significance of the south Connemara Granites for Siluro-Devonian global plate tectonics.

GEOLOGIC SETTING

The Galway Granite intruded into the metagabbros of the Dalradian Connemara complex to the north (Leake, 1989) and greenschist facies Lower Ordovician rocks to the south (Williams et al. 1988). The 80 km long, WNW-ESE-trending axis of the batholith lies on the Skird Rocks Fault, which is a western extension of the Southern Uplands Fault. These major strike-slip faults

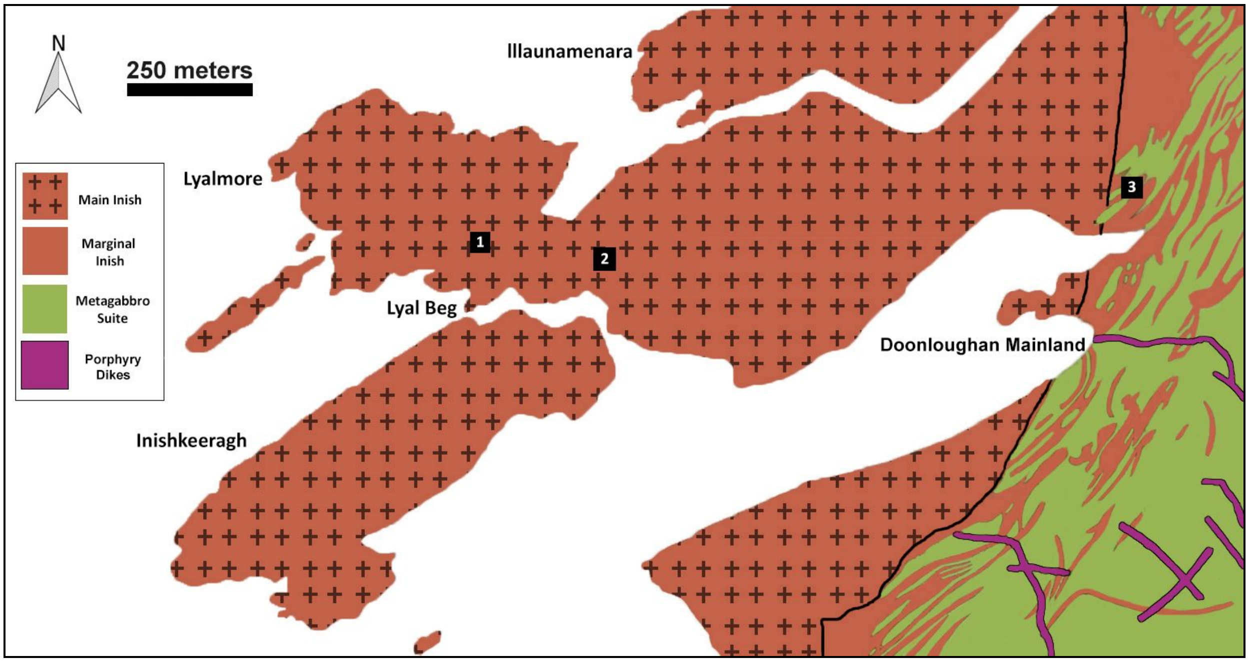

Figure 1. Geology of the main and marginal Inish Granite, as well as the Errismore metagabbro sheet to the East of the sampling site. Several quartz-feldspar porphry dikes that cross-cut the marginal granite but not the main granite are shown in purple. Sampling locations of main Inish Granite (1, 2) and marginal Inish Granite (3) are indicated with black squares. Samples 1 and 2 lie on islands Lyalmore and Lyal Beg, respectively. Sample three was taken on the shore of the mainland of Doonloughan.

are a result of the closing of the Iapetus Ocean between Laurentia and Avalonia (Dewey and Strachan, 2003; Leake, 1978). The Shannawona Fault and the Barna Fault divide the Galway Batholith into three blocks, but appear to be of local significance only.

The Galway Granite and the Omey and Roundstone satellite plutons show evidence of disseminated and quartz-vein hosted molybdenite mineralization (Feely et al., 2010). Several studies have dated the molybdenite-bearing veins at Mace Head and Murvey, along the western end of the Galway Granite (Derham, 1986; Derham & Feely, 1988; Max & Talbot, 1986; Gallagher et al. 1992; Fig. 1). The Re-Os ages for Mo mineralization at Mace Head and Murvey, 407 Ma and 410 Ma, respectively, fit well into the age range of the batholith determined by U-Pb zircon geochronology (Feely et al., 2003). Thin quartz veins in the Omey Granite (<5 cm across) host disseminated molybdenite that gives a model Re-Os age of deposition around 422 Ma, which is about 20 Ma older than the established younger Mo mineralization in the Galway Batholith (Feely et al., 2010). These authors speculated that the molybdenite mineralization of the Inish, Letterfrack, and Roundstone satellite plutons occurred around the same time as the Omey Granite. However, due to the 10 Ma difference between the model Re-Os age of the Galway Granite and its satellite pluton as well as the lack of precise U-Pb geochronology to support the model age, it is problematic to take 422 Ma as the true Mo mineralization age of the Omey Granite.

The Inish Granite outcrop located in this study site has not previously been sampled for age analysis. Faure and Powell (1972) used Rb-Sr dating to determine an age of 404 Ma for the entire Inish pluton; however, the recent model age of 422 Ma for the Omey Granite (Feely et al., 2010) suggests that the Rb-Sr age for the Inish pluton was partially reset. Field relations also show two different compositions and two possible ages for the main and marginal facies of the Inish Granite (Figure 1).

The Inish Granite intruded the southern limb of the Connemara antiform, causing folding and hornfels-facies contact metamorphism (Townend, 1966, Leake, 1985). Evidence for this comes from several NE trending folds in the metagabbro sheet that are interpreted to have formed during intrusion of the Inish Granite. The Inish granite cuts the Errismore metagabbro sheet, part of the Roundstone-Errismore-Gowla metagabbro intrusion, which crops out to the east of the pluton (Leake, 1986). The numerous sills and quartz-feldspar porphyry dikes in the eastern marginal granite around Doonloughan (Figure 1) that are lacking in the western main granite suggest that the marginal granite intruded, then dikes and sills, followed by the main Inish Granite.

The Inish Granite is a biotite-hornblende adamellite (5-20 modal% quartz with approximately equal modal abundances of plagioclase and K-feldspar), and is divided into two main phases that are not correlative with the marginal and main facies; the Inishturk adamellite and the Inish adamellite (Townend, 1966). The Inishturk adamellite crops out in the northeast and is characterized by the occurrence of both biotite and minimal hornblende. In the southeast, the Inish adamellite lacks hornblende and has smaller K feldspar porphyroblasts than the Inishturk (typically 6 x 5 x 4 mm); Townend, 1966). This study focuses on the Inish adamellite, specifically the outcrop on islands Lyall Mon and Lyall Beg (Figure 1).

METHODS

Sampling

Two samples of the main Inish granite and one sample from the fringing granite were collected for zircon U-Pb geochronology. Accessibility is limited for this area of Connemara due to the quickly rising tides that cover the exposure of this satellite pluton. Sampling was focused as far away from the mainland as possible for the main granite and close to the shore for the fringing granite. Six to seven samples were cut with a rock saw at each of the three sampling sites.

U-Pb Zircon Geochronology

All samples were crushed using a jaw crusher and disk mill and then separated using a water table. In order to isolate the zircons, the heavy separates from the water table went through a process of magnetic separation and heavy liquid separation. Zircons were then hand-picked on the basis of clarity and size, and thermally annealed for 48 hours at 900°C. Thermal annealing heals small cracks and fission tracks in the zircons. After thermal annealing, zircons from the main granite were chemically abraded in HF and HNO_3 for 4 hours at 180°C in order to eliminate volumes subject to Pb-loss and dissolve inclusions. Chemical abrasion was limited to 4 hours because initial, longer abrasion steps resulted in complete dissolution of the grains. The fringing granite, was chemically abraded on a hot plate at 150°C for 6 hours rather than in the oven in order to allow for even more gentle treatment for the crystals. After chemical abrasion, the zircons were separated into individual grains, dissolved in HF and HNO_3, and spiked using tracer enriched in ^{205}Pb-^{233}U-^{236}U. The zircons were converted to chlorides and passed through anion exchange columns in order to isolate U and Pb. Purified U and Pb were loaded separately in silica gel and run on single Re filaments. Uranium was run as an oxide and Pb was run as a metal. The samples were analyzed in single collector mode using the Daly ion-counting photomultiplier system on the IsotopX Phoenix-X62 thermal ionization mass spectrometer (TIMS) in the Department of Geological Sciences at the University of North Carolina, Chapel Hill.

RESULTS

Zircons from both samples contained many inclusions that were visible in the microscopic view while preparing for U-Pb geochronology. All data from the main granite are concordant within uncertainty (Figure 2; Table 1), whereas all data from the marginal granite are discordant (Figure 3; Table 2).

Main Inish Granite

Five zircons from the main granite are concordant, with zircon 3 lying on concordia with the smallest error. The zircons range in age from 427.69 to 421.15 Ma, with youngest and oldest limits defined by single grains, and three individual zircons clustering around 423 Ma. Zircons 1 and 4 had high common lead concentrations of 8 pg and 6 pg, respectively, which could have been caused by contamination during zircon preparation. Conversely, zircons 2, 3, and 5 had low concentrations of 2 pg, 1 pg, and <1 pg, respectively. Zircons 1 and 2 deviate from the cluster of ages on concordia, suggesting minor Pb-loss and inheritance, respectively. It is unlikely that zircons 3, 4, and 5 experienced inheritance or Pb-loss, as that would suggest that all three of them were impacted identically. Consequently, zircons 1 and 2 are not interpreted to yield data with any age significance, and the weighted mean age of the cluster of zircons 2, 3, and 5

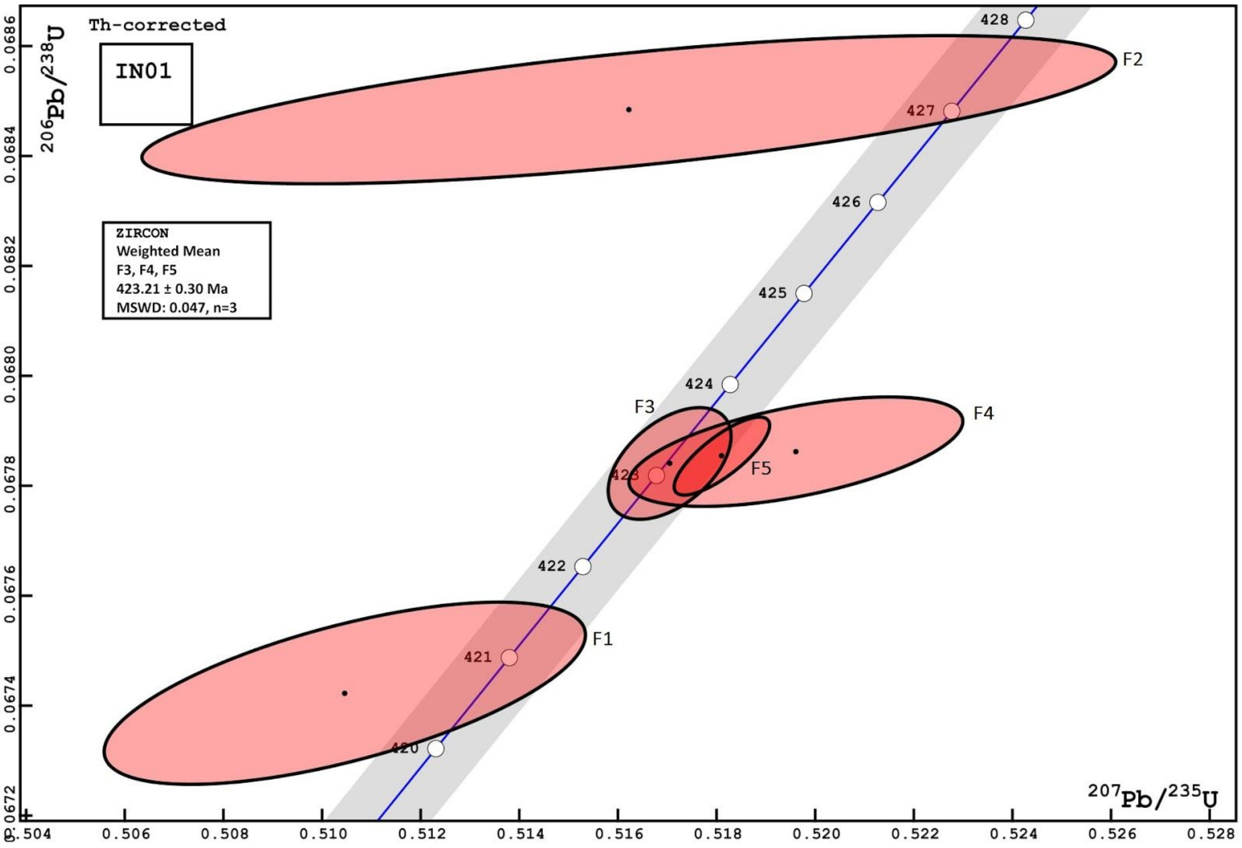

Figure 2. Concordia diagram of five single zircon samples from the main Inish Granite. All dates (in Ma) are concordant within uncertainty. Due to their deviations from the cluster of three zircons around 423 Ma, samples IN01-1 and IN01-2 were assumed to be subject to Pb-loss and inheritance, respectively, and were not included in age determinations. Consequently, the weighted mean age of samples IN01-03, IN01-04, and IN01-05 (423.21 ± 0.30 Ma) is taken to be the emplacement age of the main Inish Granite.

TABLE 1: U-PB DATA FOR MAIN INISH GRANITE

	Dates (Ma)								Composition				Isotopic Ratios						
[illegible]	^{206}Pb/ ^{238}U	±2σ abs	^{207}Pb/ ^{235}U	±2σ abs	^{207}Pb/ ^{206}Pb	±2σ abs	Corr. coef.	% disc	Th/ U	Pb* (pg)	Pbc (pg)	Pb*/ Pbc	^{206}Pb/ ^{204}Pb	^{208}Pb/ ^{206}Pb	±2σ %	^{207}Pb/ ^{206}Pb	±2σ %	^{207}Pb/ ^{235}U	±2σ %
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

a Isotopic dates calculated using λ_{238} = 1.55125E-10 (Jaffey et al. 1971) and λ_{235} = 9.8485E-10 (Jaffey et al. 1971).

b % discordance = 100 - (100 * (^{206}Pb/^{238}U date) / (^{207}Pb/^{206}Pb date))

c Th contents calculated from radiogenic ^{208}Pb and ^{230}Th-corrected ^{206}Pb/^{238}U date of the sample, assuming concordance between U-Th and Pb systems.

d Total mass of radiogenic Pb.

e Total mass of common Pb.

f Ratio of radiogenic Pb (including ^{208}Pb) to common Pb.

g Measured ratio corrected for fractionation and spike contribution only.

h Measured ratios corrected for fractionation, tracer and blank.

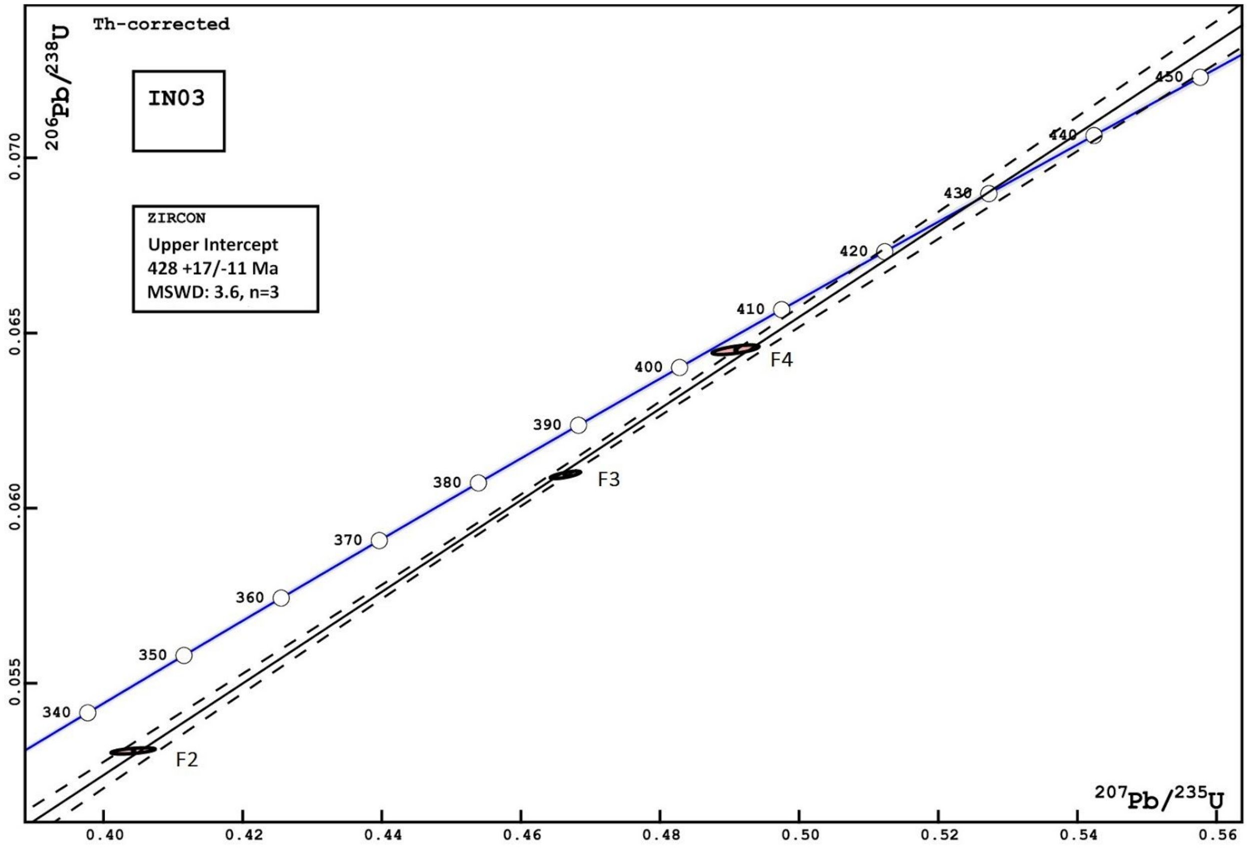

Figure 3: Concordia diagram with plotted upper-intercept projection (428 +17/-11 Ma) of three single zircon samples from the marginal Inish Granite. All samples are discordant, presumably due to Pb-loss that was a consequence of the less aggressive chemical abrasion.

TABLE 2: U-PB DATA FOR MARGINAL INISH GRANITE

	Dates (Ma)								Composition				Isotopic Ratios						
Fraction	^{206}Pb/^{238}U a	±2σ abs	^{207}Pb/^{235}U a	±2σ abs	^{207}Pb/^{206}Pb a	±2σ abs	Corr. coef.	% disc b	Th/U c	Pb* (pg) d	Pbc (pg) e	Pb*/Pbc f	^{206}Pb/^{204}Pb g	^{206}Pb/^{238}U h	±2σ %	^{207}Pb/^{235}U h	±2σ %	^{207}Pb/^{206}Pb h	±2σ %
ZIRCON																			
F-2	333.2477304	0.5490622999	344.7239457	2.296901053	422.8200229	15.70098653	0.5686110492	21.18449638	0.4492666071	68.04039615	3.073097556	22.1406561	1387.139695	0.05305456896	0.1690563568	0.4042472274	0.785794349	0.05526154015	0.7028043017
F-3	381.3080654	0.6574189662	388.6945792	1.501214461	432.8963232	7.902683883	0.7376819554	11.91700069	0.3280708695	36.01887665	0.7722786	46.63974458	2996.916185	0.06093480781	0.1775608748	0.4663933114	0.4648480207	0.05551183621	0.3532568785
F-4	402.9746277	0.8302300867	405.4985328	2.286271109	419.899266	12.62260393	0.6648477844	4.030642508	0.336061676	75.35672849	2.816809333	26.75251307	1723.941523	0.06450663586	0.2125319574	0.490863124	0.6838725679	0.05518928136	0.5643942698

a Isotopic dates calculated using λ^{238} = 1.55125E-10 (Jaffey et al. 1971) and λ^{235} = 9.8485E-10 (Jaffey et al. 1971).
b % discordance = 100 - (100 * (^{206}Pb/^{238}U date) / (^{207}Pb/^{206}Pb date))
c Th contents calculated from radiogenic ^{208}Pb and ^{230}Th-corrected ^{206}Pb/^{238}U date of the sample, assuming concordance between U-Pb Th-Pb systems.
d Total mass of radiogenic Pb.
e Total mass of common Pb.
f Ratio of radiogenic Pb (including ^{208}Pb) to common Pb.
g Measured ratio corrected for fractionation and spike contribution only.
h Measured ratios corrected for fractionation, tracer and blank.

(423.21 ± 0.30 Ma) is interpreted to be the intrusion age of the main granite.

Marginal Inish Granite

Zircons 2, 3, and 4 of the five zircons from the marginal granite were all discordant. Regression of a line through the three discordant points yields an upper intercept age of 428 +17/-11 Ma. All three zircons are interpreted to have been experienced Pb-loss that was not successfully mitigated by the less aggressive chemical abrasion that was used for this sample. Although there is significant uncertainty in the age, it is permissible that the marginal granite yields an age that is greater than the age of the main granite – consistent with the field relations.

DISCUSSION

Relation of the Satellite Plutons to the Galway Granite

New U-Pb zircon ages for the Inish Granite presented in this study provide evidence for the intrusive history of the Galway Batholith and its satellite plutons. The Inish Granite yields a weighted mean age of 423.21 ± 0.30 Ma, which is approximately 19 Ma older than the age reported by Faure and Powell. This date is the oldest reported high precision date so far for the satellite plutons of the Galway Granite, and helps to confirm the slightly younger Re-Os age for the Omey Granite (422.5 ± 1.7 Ma). The new date also supports the claim that assembly of the Galway plutons occurred over a span of at least 40 Ma, beginning around 423 Ma (or perhaps as old as 430 Ma if the age for the marginal facies of the Inish Granite stands) with the intrusion of the Inish Granite and ending around 380 Ma with the latest assembly of the Galway Batholith (Feely et al., 2010). This assembly of older plutons surrounding a younger batholith is similar to the incremental emplacement of the Tuolomne intrusive suite, where ages decrease towards the center of the suite (Coleman et al., 2004).

Field Relations Between the Galway Batholith and Porphyry Dikes

The quartz-feldspar porphyry dikes that cross-cut the marginal, but not the main, Inish granite were assumed to be associated with the final pulse of the Galway Granite (i.e., < 380 Ma), suggesting that the main Inish granite was emplaced later than the Galway Granite (Leake, 1986). However, U-Pb data show emplacement of the Inish around 423 Ma, at least 10 Ma before emplacement for the Galway Granite (410 Ma-380 Ma). This discrepancy demands that there are multiple generations of porphyry dikes. Thus, caution should be exercised when hypothesizing relative age relations in the region on the basis of the occurrence of the dikes.

Molybdenite Mineralization in the Connemara Granites

The precise U-Pb age of the Inish Granite determined in this study indicate that the model Re-Os age of 422 Ma for the Omey Granite is reasonable. The approximate 10 Ma gap from the late stage Mo mineralization in the Galway Granite (400 Ma) and the Omey Granite (422 Ma) provides evidence of multiple episodes of Mo mineralization in the south Connemara Granites. Although there are no present geochemical analyses to support Mo mineralization in the Inish Granite, the location of the four satellite plutons in relation to the Galway Granite allows for the correlation of U-Pb ages from the Inish Granite with the time of emplacement of the Omey, Roundstone, and Letterfrack plutons.

Paleogeography Considerations

Northwestern Ireland resided on Laurentia during the assembly of the Galway Granite and its satellite plutons (Cocks and Torsvik, 2006). The confirmed range of ages for the south

Connemara Granites from this study is identical to that of the Siluro-Devonian plutons and associated volcanic rocks in southeastern New England, USA (Figure 3; Thompson et al, in review). These alkalic plutons were hypothesized to be caused by oblique convergence of Laurentia and Avalonia. Newly determined ages for this suite range from 426 to 378 Ma, with an age of 422.99 ± 0.51 Ma for the Newbury Volcanic Complex of northernmost Massachusetts that formed in the mid-Paleozoic Laurentian margin in southeastern New England. Combining these results with the equivalent ages of the calc-alkaline Inish and Omey granite (423 Ma and 422 Ma, respectively) supports the hypothesis that subduction of West Avalonia underneath Laurentia during the closing of the Iapetus Ocean took place in the mid-to Late Silurian period (Figure 4). This link between intraplate rifting on West Avalonia and long-lived emplacement of south Connemara granites on the overlying plate of Laurentia suggests that both were caused in part by the convergence of the two land masses, and that magmatism ended with the final collision of Laurentia and Avalonia. This suggests that the age for the complete closure of the Iapetus Ocean is around 380 Ma.

CONCLUSIONS

These new reported ages for the Inish Granite confirm the recent model Re-Os molybdenite ages of the Omey Granite, and show that the emplacement of the south Connemara Granites extended from at least 423 Ma to 380 Ma. This span of around 40 Ma for emplacement indicates a long-lived period of granite emplacement. The field relations of the Inish Granite show a history of emplacement beginning with the marginal granite, followed by the quartz-feldspar porphyry dikes, and ending with the main granite. Similarities between the ages of the south Connemara Granites and the Paleozoic alkalic suites in southeastern New England

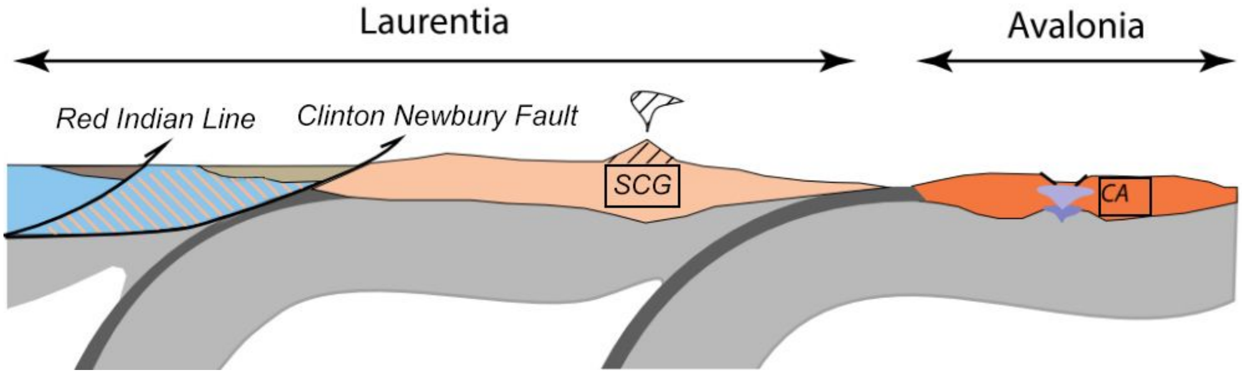

Figure 4: Adapted from Thompson et al., in review. Model showing Avalonia subduction underneath Laurentia during the mid-to Late Silurian time period. SCG-South Connemara Granites and CA-Cape Ann Pluton are indicated on Laurentia and Avalonia, respectively.

give further confirmation for the proposed tectonic history of Avalonia subduction underneath Laurentia, with the last traces of magmatism in both suites (around 380 Ma) indicating the final closure of the Iapetus Ocean.

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