CONSTRAINING SINISTRAL SHEARING IN NW IRELAND: A PRECISE U–Pb ZIRCON CRYSTALLISATION AGE FOR THE OX MOUNTAINS GRANODIORITE

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Abstract

The age of the Ox Mountains Granodiorite has proved controversial in the past. Two published Rb–Sr whole rock isochrons suggest ages of 487 ± 6 Ma and 500 ± 18 Ma, respectively (λ^{87}Rb = 0.0139 Ga^{-1}), whereas Rb–Sr muscovite–feldspar isochrons from undeformed pegmatites associated with the intrusion have yielded *c*. 400Ma ages. The syn-kinematic nature of the Ox Mountains Granodiorite has been clearly demonstrated by several workers, with the pluton being emplaced as a series of sheets in a major transpressive sinistral shear zone. Knowledge of the age of crystallisation of the Ox Mountains Granodiorite would thus constrain the timing of strike-slip movement along this shear zone, which forms part of a major Caledonide structure known as the Fair Head – Clew Bay Line. A U–Pb zircon age (conventional isotope dilution TIMS) of 412.3 ± 0.8 Ma from a tonalitic facies of the pluton is presented here. The age confirms that emplacement was broadly contemporaneous with the majority of other volumetrically important Irish granite batholiths (i.e. Leinster, Donegal, Galway and Newry), while $\epsilon Hf_{(412)}$ values of the dated zircons (which range from –5.4 to –7.7) imply incorporation of old crustal material into the parent melt.

Introduction

The Ox Mountains Granodiorite crops out as an elongate, NE–SW trending pluton, about 25km long and 5km wide in NW Ireland (Figs 1a, 2), and is the most volumetrically important member of the Ox Mountains Igneous Complex (McCaffrey 1989). It is intruded into polyphase-deformed metamorphic rocks of the Dalradian Supergroup (the Central Ox Mountains Inlier), and postdates regional amphibolite facies metamorphism that occurred during the Grampian orogeny (Yardley *et al*. 1987). The Central Ox Mountains Inlier lies at the south-eastern margin of the main Dalradian outcrop in Ireland, which is in general delimited by a major terrane-bounding suture, the Fair Head – Clew Bay Line (Figs 1a, 1b), along which multiple episodes of shearing have taken place (Chew *et al*. 2004 and references therein).

Structural timing of intrusion

Early studies (e.g. Currall and Taylor 1965; Phillips *et al*. 1975) recognised that the intrusion post-dated at least two phases of deformation and was intruded contemporaneously with

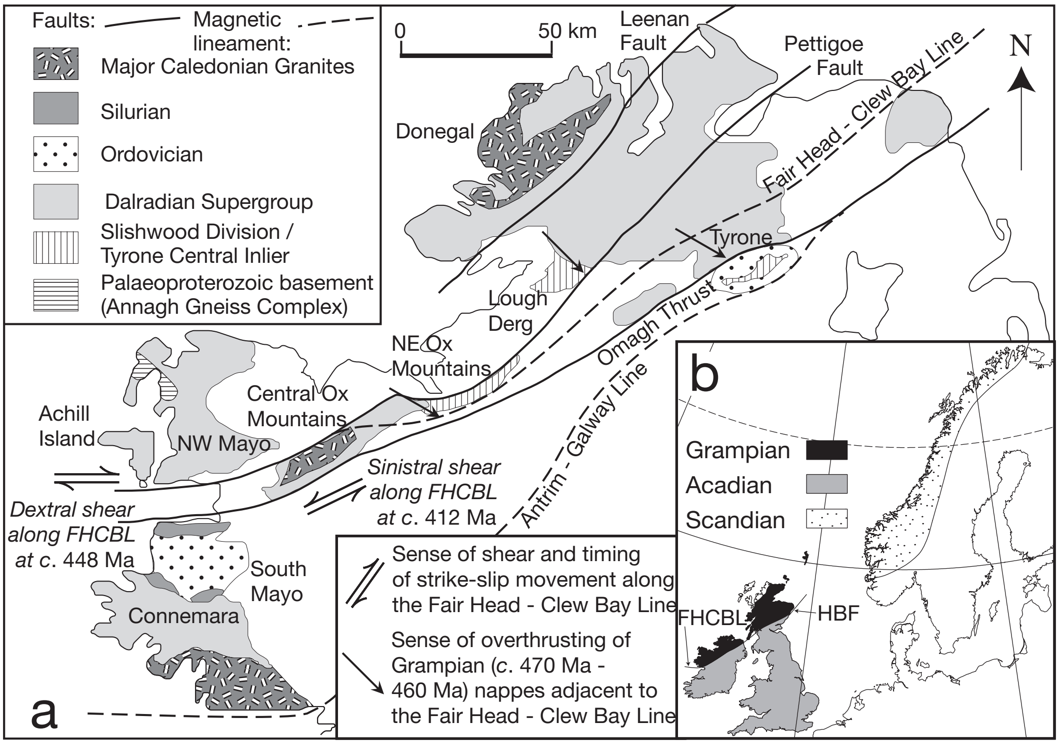

Fig. 1—A) Geology of NW Ireland with the Fair Head – Clew Bay Line and major Caledonian Granites illustrated; B) location of the Fair Head – Clew Bay Line in the Caledonian Belt.

respect to the third phase of deformation. The pluton was intruded into the core of a major upright D3 antiform developed within the Dalradian metasediments (Fig. 2), which trends north-east–south-west, subparallel to the length of the inlier (Taylor 1969). High strain zones are well developed on the limbs of the main D3 antiformal structure and are parallel to the vertical, axial planar S3 fabric. These high strain zones contain kinematic indicators such as rotated porphyroblasts and extensional crenulation cleavages that display abundant evidence for sinistral shear (e.g. Hutton and Dewey 1986; Hutton 1987; Jones 1989; McCaffrey 1992; 1994; Chew *et al.* 2004). These shear zones have been regarded as contemporaneous with the development of the main D3 antiform, and hence the Central Ox Mountains Inlier has been regarded as a transpressive sinistral shear zone during D3 (Hutton and Dewey 1986; Hutton 1987; Jones 1989; McCaffrey 1992; 1994). A detailed summary of the structural history of the Central Ox Mountains Inlier (along with some slight modifications to the chronology outlined above) is given in MacDermot *et al.* (1996).

The Ox Mountains Granodiorite itself also displays abundant evidence of sinistral strike-slip deformation. The main solid-state foliation is sub-vertical, strikes north-east–south-west and is accompanied by a stretching lineation that plunges gently to the north-east or south-west (McCaffrey 1992; 1994). North–north-east trending sinistral S–C fabrics are commonly well developed within the granodiorite and are subparallel to the asymmetrical extensional crenulation cleavages developed in the country rock (Hutton and Dewey 1986; McCaffrey 1992; 1994). The Ox Mountains Granodiorite has thus been regarded as being emplaced syn-kinematically with respect to D3 sinistral transpressive deformation in the country rock (Hutton and Dewey 1986; Jones 1989; McCaffrey 1992; 1994), while space for granite emplacement was facilitated by transient, local dilational sites in an overall transpressive regime (McCaffrey 1992).

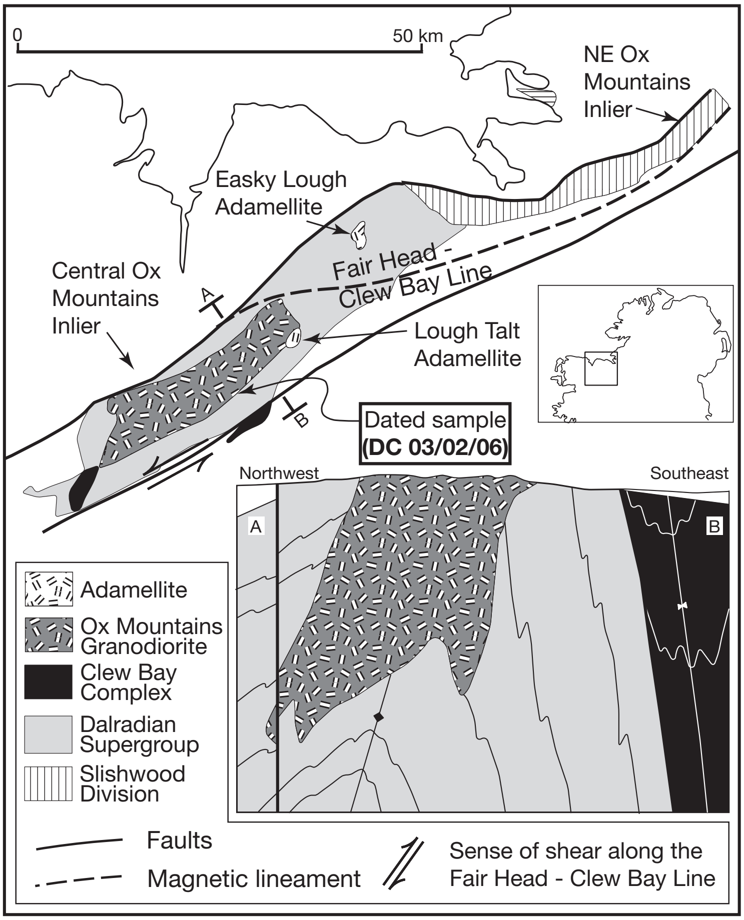

Fig. 2—Geology and cross section of the Ox Mountains, adapted after MacDermot *et al.* 1996.

Component lithologies and intrusion mechanism
McCaffrey (1989; 1992) recognised that the Ox Mountains Granodiorite is comprised of four main components. These are (in order of intrusion): (1) small muscovite granite sheets, (2) granodiorite (both equigranular and K-feldspar megacrystic varieties), (3) diorites and (4) tonalites. Of these, the granodiorites (and in particular the equigranular facies) are by far the most important volumetrically. McCaffrey (1989; 1992) proposed that the pluton was emplaced as a sequentially intruded series of sheets. Where there is clear compositional variability at an outcrop scale, the sheeted nature of the intrusion is immediately apparent. These sheeted zones include sheeted contacts with the country rock and the spectacular sheeted tonalitic–granodiorite exposures at Pontoon in the SW corner of the pluton (McCaffrey 1992; 1994). It is thus possible, or even probable, that the more compositionally homogeneous portions of the intrusion (such as the core, which is composed almost entirely of equigranular granodiorite) were also intruded in a sheet-like manner.

Pre-existing age constraints on the Ox Mountains Granodiorite

There are two published Rb–Sr whole rock isochrons for the Ox Mountains Granodiorite, with ages of 487 ± 6 Ma (Pankhurst *et al*. 1976) and 500 ± 18 Ma (Max *et al*. 1976). Recalculated for λ^{87}Rb = 0.0142 Ga^{-1} (Steiger and Jäger 1977), these ages become 477 ± 6 Ma and 489 ± 18 Ma, respectively.

However, several lines of evidence mitigate against a *c*. 480Ma intrusion age. From a regional tectonic point of view, the ages quoted above would imply that granite intrusion (and thus the last phases of regional deformation) took place at *c*. 480Ma. Yet the main phase of Grampian orogenic activity in Ireland and Scotland started at about 475Ma and continued until approximately 465Ma (Soper *et al*. 1999).

Other lines of evidence suggest that a *c*. 405Ma intrusion age for the Ox Mountains granodiorite is more likely. Two satellite plutons (the Lough Talt and Easky Lough adamellites) of the Ox Mountains igneous complex have yielded a composite 400 ± 33 Ma isochron (Long and O'Connor 1984), while pegmatites associated with the Ox Mountains Granodiorite have yielded four Rb–Sr muscovite-feldspar ages that range from 402–392Ma, and are interpreted as recording igneous crystallisation (Flowerdew *et al*. 2000). Additionally, mineral cooling ages as young as *c*. 410Ma have been obtained from the Dalradian country rock close to the Ox Mountains Granodiorite (Flowerdew *et al*. 2000). Grampian cooling ages from the same region cluster between 460–450Ma, and therefore the younger set of cooling ages have been attributed to thermal resetting by the Ox Mountains Granodiorite (Flowerdew *et al*. 2000).

Analytical methods and data

Sample location and description

Sample DC 03/02/06 comes from the sheeted contact between the pluton and the country rock contact approximately 3km NNE of Callow Lough Lower (Irish National Grid ref. G325058). The country rock comprises of Dalradian quartzites and psammites (locally termed the Leckee Quartzite Formation) and is intruded by several large granodiorite sheets, up to 30m wide. The granodiorite sheets increase in frequency to the NW as the main body of the

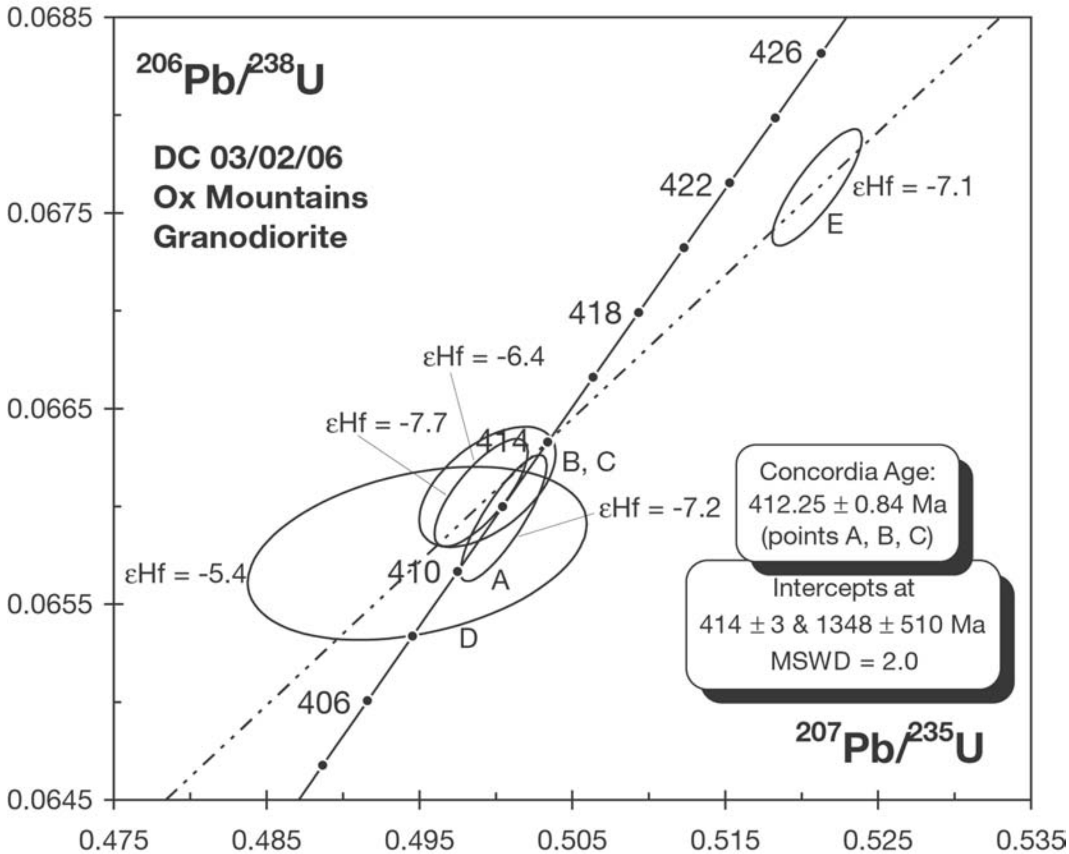

Fig. 3—U–Pb concordia diagram for the dated sample DC 03/02/06.

pluton is approached (fig. 7 of Chew *et al*. 2004), and thus the country rock–pluton contact is gradational in nature at this locality. The dated sample is classified as a tonalite using the QAP plot of Streckeisen (1976), with plagioclase = 51%, K-feldspar = 4.5% and quartz = 44.5%. It is moderately deformed, with a foliation defined by aligned biotite and ribboned quartz. Zircons were separated from a 1kg granodiorite sample by conventional means. The sub-300µm fraction was processed using a Wilfey table, and then the Wilfey heavies were passed through a Frantz magnetic separator at 1A. The non-paramagnetic portion was then placed in a filter funnel with diiodomethane. The resulting heavy fraction consisted of > 99% zircon, with a yield of several hundred grains. This fraction was then passed again through the Frantz magnetic separator at full current and a side slope of 1°. Zircons selected from the abraded, non-paramagnetic fraction exhibit two morphologically distinct populations. Both populations feature {211} bipyramids, with the first population being characterised by long prismatic grains, with aspect ratios of up to 5:1, and the second population consisting of smaller, more equant grains, that often contain abundant inclusions.

Analytical technique

The zircon grains were washed in dilute HNO_3 and rinsed several times in distilled water and acetone in an ultrasonic bath. A mixed ^{205}Pb–^{235}U spike was added prior to dissolution in a mixture of HF and HNO_3 using steel-jacketed Teflon bombs. Chemical separation of Pb and U was done on anion exchange resin using minimal amounts of ultra-pure acids. Isotopic analysis was performed on a MAT262 mass spectrometer equipped with an ion-counting system. The latter was calibrated by repeated analysis of the NBS 982 standard using the 208/206 ratio of 1.00016 for mass bias correction (Todt *et al*. 1996). Total procedural Pb blank was estimated at 0.8 ± 0.5 pg. Common lead in excess of this amount was corrected with the model of Stacey and Kramers (1975) for the respective ^{206}Pb/^{238}U age of the zircon. The uncertainties of the isotopic composition of the spike, blank and common lead were taken into account and propagated to the final uncertainties of isotopic ratios and ages. Ages were calculated using ISOPLOT (Ludwig 1999). Ellipses in the concordia diagram (Fig. 3) represent 2-sigma uncertainties. The Hf fraction was isolated from the Zr + Hf + REE fraction of the Pb column chemistry using Eichrom Ln-spec resin and measured in static mode on a NuPlasma multi-collector ICP-MS using an Aridus nebuliser for sample introduction. The Hf isotopic values were corrected for a 176Lu/177Hf of 0.0005, typical of zircon. The Hf isotopic ratios were corrected for mass fractionation using a 179Hf/177Hf value of 0.7325 and normalised to 176Hf/177Hf of 0.28216 of the JMC-475 standard. The isotopic ratios for the CHUR are those of Blichert-Toft and Albarède (1997).

Results

Three single grains and two microfractions of three grains devoid of inclusions and impurities have been analysed: the data are presented in Table 1 and Fig. 3. Fractions A, B and C were selected from the long prismatic population, while Fractions D and E were chosen from the short prismatic population. Analyses A to D yielded analytically concordant points: analysis D is biased by a high proportion of common lead in analysis and is thus discarded from the age calculation. A concordant age of 412.3 ± 0.8 Ma (95% confidence level) has been calculated from analyses A to C. The point E is discordant and very likely reflects the presence of an inherited component of mid-Proterozoic age in this grain, albeit with a large error on the upper intercept. It is felt likely that this grain was inherited from either the Dalradian country rock or its basement. Although detrital zircons from the Dalradian metasediments exhibit a wide range of ages, a major peak in the ages ranges from the late Palaeoproterozoic (~ 1.8Ga) to the early Mesoproterozoic (~ 1.5Ga) (Cawood *et al*. 2003).

The Hf isotopic compositions (Table 2) were determined from the same zircon microfractions used for U–Pb dating (Table 1). Owing to the very low ^{176}Lu/^{177}Hf ratios in zircon, they represent initial Hf isotopic compositions at the time of melt crystallisation. Precise U–Pb dating combined with the determination of initial Hf isotopes in dated zircons is thus a powerful

Table 1—Hf isotopic data on zircon from the Ox Mountains Granodiorite

Sample	*$^{176}Hf/^{177}Hf$*[1]	± 2δ	*$^{176}Hf/^{177}Hf$*[2] *(T)*	*εHf*[3]	±2δ *(T)*	*$T_{(DM)}$*[4] *(Ga)*
DC-02/03-6A	0.282306	0.000012	0.282302	–7.2	0.5	1.7
DC-02/03-6B	0.282291	0.000007	0.282287	–7.7	0.5	1.7
DC-02/03-6C	0.282328	0.000007	0.282324	–6.4	0.5	1.7
DC-02/03-6D	0.282358	0.000007	0.282354	–5.4	0.5	1.6
DC-02/03-6E	0.282309	0.000012	0.282305	–7.1	0.5	1.7

1 Corrected for mass fractionation using a $^{179}Hf/^{177}Hf$ value of 0.7325 and normalised to $^{176}Hf/^{177}Hf$ = 0.282160 of the JMC-475 standard (Blichert-Toft and Albarède *et al*. 1997).
2 Calculated using an age of 412Ma.
3 Epsilon Hf values were calculated with a $^{176}Hf/^{177}Hf$ (CHUR) value of 0.282772 (Blichert-Toft and Albarède 1997).
4 Calculated with present-day DM values of 176Hf/177Hf=0.283252, 176Lu/177Hf=0.04145 and a crustal 176Lu/177Hf=0.017 (Blichert-Toft and Albarède 1997).

Table 2—U–Pb isotopic results from zircon of the Ox Mountains Granodiorite

Sample no.	*Description*[1]	*Weight (mg)*	*No. of grains*	*Concentrations*			
				U (ppm)	*Pb rad. (ppm)*	*Pb non-rad. (pg)*	*Th/U*[2]
A	pr zir frags	0.0080	3	290	20.10	4.0	0.52
B	euh zir pr	0.0036	1	395	26.22	2.6	0.36
C	euh zir pr	0.0066	1	140	9.98	4.0	0.62
D	spr zir	0.0028	1	283	18.53	15.3	0.34
E	spr zir, small incl	0.0033	3	418	28.70	1.9	0.38

Sample no.	*Description*[1]	*Apparent ages*			*Error corr.*
		206/238[4]	*207/235*[4,5]	*207/206*[4,5]	
A	pr zir frags	411.6	412.0	414.4	0.84
B	euh zir pr	412.4	411.1	403.2	0.76
C	euh zir pr	412.6	411.3	404.0	0.55
D	spr zir	410.6	408.2	395.0	0.34
E	spr zir, small incl	421.9	425.8	447.0	0.84

1 zir = zircon; euh = euhedral, frags = fragments, incl = inclusions, pr = prisms, spr = short prismatic.
2 Calculated on the basis of radiogenic Pb^{208}/Pb^{206} ratios, assuming concordancy.
3 Corrected for fractionation and spike.
4 Corrected for fractionation, spike, blank and common lead (Stacey and Kramers 1975)
5 Corrected for initial Th disequilibrium, using an estimated Th/U ratio of 4 for the melt.

tool for tracing magmatic events, as it yields information on both the age of crystallisation and the source of the magmatism. In general, the geochemical properties of Lu and Hf are similar to those of Sm and Nd because Hf is concentrated relative to Lu in silicate liquids. Thus Hf model ages can be calculated in a manner analogous to the Sm–Nd system, and reflect the time elapsed since a melt was separated from its source reservoir (usually assumed to be either CHUR or depleted mantle). Epsilon Hf values of the dated zircons range from –5.4 to –7.7 (Table 2). These low values imply incorporation of old crustal material into the parent melt, as also suggested by the presence of inherited cores in the dated zircons.

Discussion: implications of the new age for the Ox Mountains Granodiorite

The new concordant U–Pb zircon age of 412.3 ± 0.8 Ma is interpreted as the crystallisation age of the granodiorite. This confirms that intrusion was broadly contemporaneous with the emplacement of the majority of the other large Irish granite batholiths such as Leinster, Donegal, Galway and Newry (see Stillman (2001) for a summary of the age data from the Irish Caledonian intrusions). The origin of the anomalously old Rb–Sr isochrons and the tectonic implications of this new crystallisation age are now discussed.

a) Origin of the anomalously old Rb–Sr isochrons

The majority of the Ox Mountains Granodiorite Rb–Sr whole rock data of Pankhurst *et al*. (1976) are characterised by low $^{87}Rb/^{86}Sr$ values, with all but three of the twelve samples analysed having $^{87}Rb/^{86}Sr$ values <2 (Pankhurst *et al*. 1976) and an initial $^{87}Sr/^{86}Sr$ ratio of ~0.7055. Using this same initial $^{87}Sr/^{86}Sr$ ratio, the two samples with the highest $^{87}Rb/^{86}Sr$ values (samples 9a and 9b of Pankhurst *et al*. 1976) yield two point isochrons of 412 ± 6 Ma and 398 ± 6 Ma respectively. Rb–Sr whole rock isochrons characterised by low Rb/Sr values have also been obtained from other Caledonian granites, and independent evidence shows that these too have apparent ages of *c*. 480Ma ages where the intrusion is demonstrably younger (*c*. 405Ma) (Kennan 1997).

In attempting to explain the origin of these anomalously old *c*. 480Ma isochrons, the following two observations must be taken into account. Firstly, the source presumably had an initial $^{87}Sr/^{86}Sr$ isotopic composition of around 0.7055. This is taken as a minimum value for the initial $^{87}Sr/^{86}Sr$ isotopic composition of the source, as presumably it contained some Rb and its $^{87}Sr/^{86}Sr$ isotopic ratio would thus be slightly higher. Secondly, as the Ox Mountains Granodiorite preserves evidence for two separate (*c*. 480 Ma and *c*. 405Ma) Rb–Sr isotopic arrays, this would indicate a lack of Sr isotopic homogenisation during emplacement. Probably the simplest mechanism to explain these observations would involve binary mixing of more mafic (mantle-derived?) magma having an $^{87}Sr/^{86}Sr$ isotopic composition of ~0.7055 with a more evolved crustal granitic magma having an initial $^{87}Sr/^{86}Sr$ isotopic composition of ~0.709 at *c*. 412Ma. In this scenario, the older 480Ma isochron has no geological significance—it is simply an artefact of the mixing process. The lack of Sr isotopic homogenisation during intrusion could be explained by the mechanism of emplacement. Progressive emplacement of mafic sheets into an earlier, partially-to-fully crystalline granitic host is unlikely to have led to large-scale convective homogenisation of Sr isotopes.

b) Timing of movement along the Fair Head – Clew Bay Line

The Fair Head – Clew Bay Line has been shown to have had a long and complicated history of movement and has been reactivated several times (Chew *et al*. 2004). It was originally active as a ductile thrust during the (*c*. 470–460Ma) Grampian orogeny, where Dalradian nappes adjacent to the Fair Head – Clew Bay Line were thrust over outboard terranes to the southeast (Alsop 1991; Alsop and Hutton 1993). Post-Grampian dextral strike-slip movement along the Fair Head – Clew Bay Line has been documented at *c*. 448Ma in Achill Island, based on isotopic dating of fabric-forming muscovites that grew during this shearing event (Chew *et al*. 2004). This study confirms that another phase of post-Grampian strike-slip movement took place along this major Caledonian structure in the Central Ox Mountains Inlier, but at 412Ma and with a sinistral shear sense.

Conclusions

A precise U–Pb zircon crystallisation age of 412.3 ± 0.8 Ma for the Ox Mountains Granodiorite confirms that intrusion was broadly contemporaneous with the emplacement of the majority of the other large Irish granite batholiths such as Leinster, Donegal, Galway and Newry . This new zircon age confirms that the two previously published *c*. 480Ma Rb–Sr isochron ages for the Ox Mountains Granodiorite are not recording crystallisation, but are instead most likely an artefact of mixing between magmas from juvenile (probably mantle-derived) and crustal sources. The sheeted nature of the intrusion may have played a role in preventing Sr isotopic homogenisation of the pluton. As the intrusion was syn-kinematic with respect to strike-slip deformation in the country rock, the new zircon age also constrains a major phase of sinistral shearing along the Fair Head – Clew Bay Line and further illustrates the complicated reactivation history of this major Caledonian structure.

Acknowledgements

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