Current Research (2009) Newfoundland and Labrador Department of Natural Resources
Geological Survey, Report 09-1, pages 225-234

NEW CONSTRAINTS ON THE TIMING OF MOLYBDENITE MINERALIZATION IN THE DEVONIAN ACKLEY GRANITE SUITE, SOUTHEASTERN NEWFOUNDLAND: PRELIMINARY RESULTS OF Re–Os GEOCHRONOLOGY

E.P. Lynch, D. Selby[1], M. Feely and D.H.C. Wilton[2]
Department of Earth and Ocean Sciences, National University of Ireland, Galway, Ireland
[1]Department of Earth Sciences, Durham University, Science Labs, Durham DH1 3LE, UK
[2]Department of Earth Sciences, Memorial University, St. John's, NL, A1B 3X5 Canada

ABSTRACT

New Re–Os molybdenite ages are presented from three prospects (Motu, Ackley City and Wylie Hill) located along the southern margin of the Ackley Granite suite, southeastern Newfoundland. These dates provide new constraints on the timing of high-level granite emplacement and contemporaneous granophile mineralization, and also provide a comparison with previous estimates for the age of the granite and associated mineral deposition. The ages indicate a single episode of spatially related, late-stage, syngenetic mineralization at Motu (378.1 ± 1.7 Ma, n = 1), Ackley City (379.7 ± 1.7 Ma, n = 5) and Wylie Hill (380.2 ± 1.6 Ma, n = 2). The results suggest that all three prospects formed synchronously at 379.6 ± 1.7 Ma (weighted average, n = 8). The Re–Os dates are similar to, but slightly older than previous Ar–Ar magmatic and hydrothermal mica (biotite/muscovite) ages. The preliminary Re–Os dates yield a precise timing for roof-zone crystallization and syngenetic mineral deposition in the Ackley Granite suite and also support temporal correlation of the Ackley Granite with other Late Devonian (Frasnian) granitoid plutons such as the Francois and St. Lawrence granites. The presented Re–Os molybdenite geochronology has great potential in constraining the precise timing of late magmatism and associated mineralization in Newfoundland, and facilitating correlations with analogous regions in Europe and North America.

INTRODUCTION

Silurian and Devonian granitoid rocks are areally extensive within the Central Mobile Belt of the Appalachian Orogen in Newfoundland and its adjacent margins. Several of these bodies contain late-stage magmatic–hydrothermal granophile mineralization, resulting in the variable concentration of lithophile metals such as Mo, W, Sn and F. With the exception of vein-hosted fluorspar deposits of the St. Lawrence Granite, granite-hosted mineralization across Newfoundland is typically sporadic in distribution and subeconomic. However, recent exploration results indicate that some areas may include bulk-tonnage or vein-style deposits of potential economic significance (*see* Kerr *et al.*, *this volume*). The timing of such mineralization is of interest in the context of regional relationships and mineral exploration. This article describes the preliminary results of Re–Os molybdenite geochronology in the Ackley Granite, southeastern Newfoundland. It represents the first part of a wider Re–Os isotope investigation into the timing of Paleozoic granitoid magmatism and mineralization in Newfoundland.

Rhenium–osmium (Re–Os) molybdenite geochronology has developed over the last 45 years from an experimental method for absolute-age determinations (Hirt *et al.*, 1963) into a credible, robust, radiometric-dating technique (*e.g.*, Stein *et al.*, 1998; Selby and Creaser, 2001a; Mao *et al.*, 2008). Molybdenite is commonly enriched in Re (at the ppm level), but contains essentially no common Os; thus, ages can be obtained from single samples. New sample preparation techniques and analytical methods allow for precise age determinations (Stein *et al.*, 2001, 2003; Selby and Creaser, 2004). The latter has permitted the application of Re–Os molybdenite geochronology to be used widely to date individual mineral deposits, constrain the timing and length of overlapping mineralizing events, and help unravel complex tectonic/geological problems (*e.g.*, Stein *et al.*, 1997; Selby and Creaser 2001b; Bingen *et al.*, 2006).

Preliminary Re–Os molybdenite dates are presented that provide the first absolute ages for sulphide mineralization within the Ackley Granite. The data indicate that late-stage granite emplacement and mineralization were coeval.

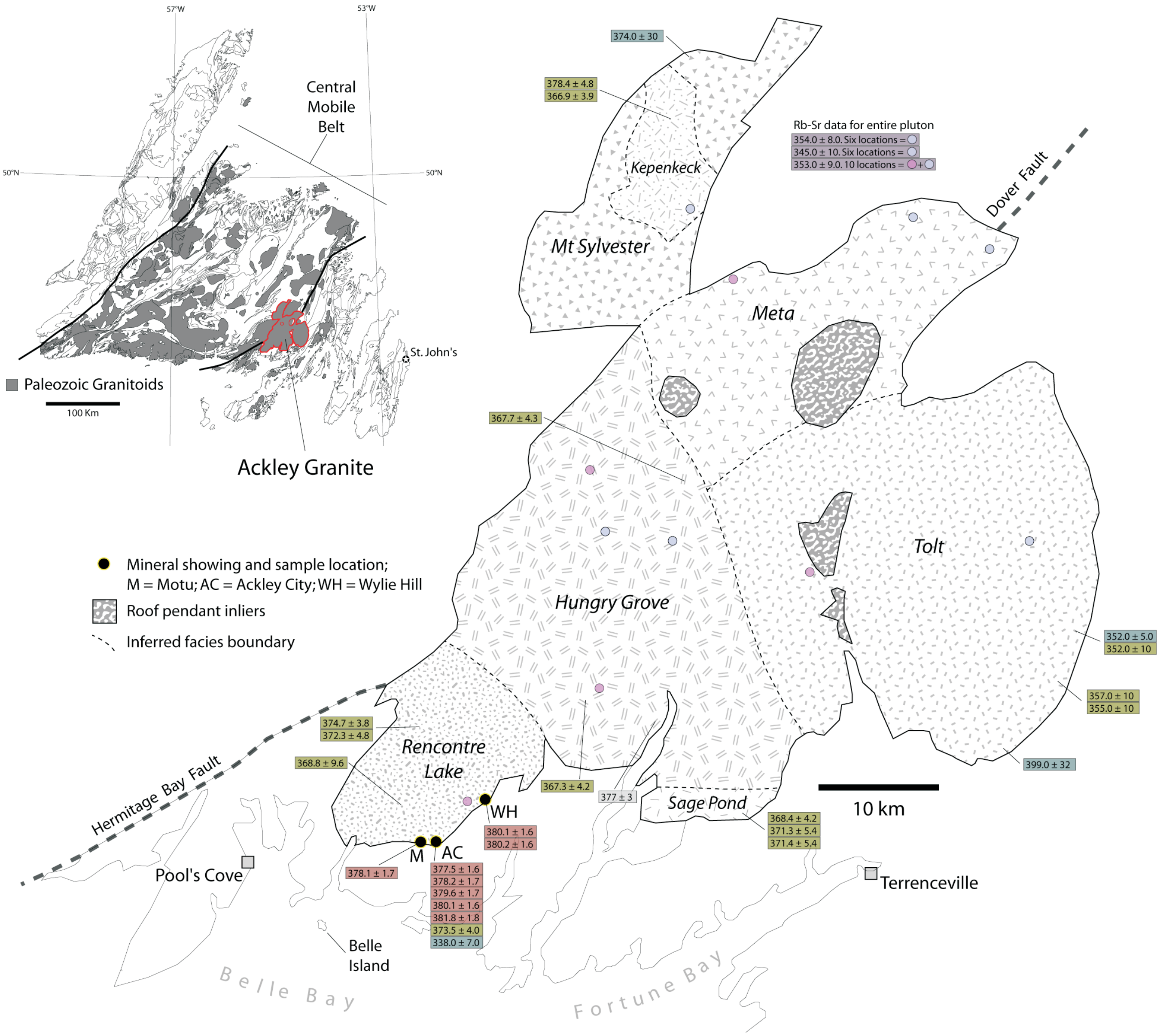

Figure 1. *Subdivisions of the Ackley Granite, showing previous and new geochronological data and the locations of the Motu, Ackley City and Wyllie Hill prospects. Modified after Colman-Sadd* et al. *(1990).*

The new Re–Os dates demonstrate the potential of the method to greatly improve constraints on the timing of late-stage plutonism in the Newfoundland Appalachians.

GEOLOGICAL SETTING AND MINERALIZATION

The Ackley Granite is a large (~2500 km^2), composite, batholith in southeastern Newfoundland (Figure 1) and represents one of the best examples of the late-stage, postorogenic Paleozoic granites on the Island. Consequently, the batholith is one of the most studied in terms of its geology (Dickson, 1983; Whalen, 1983; O'Brien *et al.*, 1984), geochemistry (Tuach *et al.*, 1986, 1988; Tuach, 1987), metallogeny (Whalen, 1976, 1980) and geochronology (Bell *et al.*, 1977; Dallmeyer *et al.*, 1983; Kontak *et al.*, 1988).

The batholith straddles a major terrane boundary between the Avalon Zone, to the east, and the Gander Zone, part of the Central Mobile Belt, in the west. This boundary, termed the Dover–Hermitage Bay Fault, represents one of the fundamental structural lineaments in the Appalachian–Caledonian Orogen. The granite is considered to represent a classic 'stitching' pluton, having intruded two tectonostratigraphic zones following their juxtaposition (Williams, 1979). The granite is subdivided into a number of

Table 1. Description of previous age determinations for the Ackley Granite

Reference	Geochrono-meter	Mineral Phase (M/H)[a]	Age (Ma ± 2σ)	MSWD	Ackley Granite Facies[b]
O'Brien 1998	U-Pb	Zircon (M)	377 ± 3[c]		Hungry Grove
Kontak *et al.* 1988	Ar-Ar	Biotite (M)	366.9 ± 3.9		Kepenkeck
	Ar-Ar	Muscovite (M)	378.4 ± 4.8		Kepenkeck
	Ar-Ar	Biotite (M)	367.7 ± 4.3		Hungry Grove
	Ar-Ar	Biotite (M)	367.3 ± 4.2		Hungry Grove
	Ar-Ar	Biotite (M)	368.8 ± 9.6		Rencontre Lake
	Ar-Ar	Muscovite (H)	373.5 ± 4.0		Rencontre Lake
	Ar-Ar	Biotite (M)	372.3 ± 4.8		Rencontre Lake
	Ar-Ar	Hornblende (M)	374.8 ± 3.8		Rencontre Lake
	Ar-Ar	Biotite (M)	368.4 ± 4.2		Sage Pond
	Ar-Ar	Muscovite (H)	371.3 ± 4.5		Sage Pond
	Ar-Ar	Muscovite (H)	371.4 ± 5.4		Sage Pond
	K-Ar	Biotite (M)	352.0 ± 5.0		Tolt
Tuach 1987	Rb-Sr	Whole rock	353 ± 9	2.4	10 sample locations: Kepenkeck = 2, Mt Sylvester = 2, Meta = 1, Hungry Grove = 2, Rencontre Lake = 2, Tolt = 1
Dallmeyer *et al.* 1983	Ar-Ar	Biotite (M)	357 ± 10		Tolt
	Ar-Ar	Biotite (M)	352 ± 10		Tolt
	Ar-Ar	Hornblende (M)	355 ± 10		Tolt
Whalen 1980	K-Ar	Muscovite (H)	338 ± 7		Rencontre Lake
Bell *et al.* 1977	Rb-Sr	Whole rock	354 ± 8[d]	1.9	Six sample locations: Kepenkeck = 1, Hungry Grove = 2, Meta = 2, Tolt = 1
Bell & Blenkinsop 1975	Rb-Sr	Whole rock	345 ± 10[e]	1.8	Four sample locations: no details reported
Leech *et al.* 1963	K-Ar	Biotite (M)	399 ± 32[d]		Tolt
Lowden 1961	K-Ar	Biotite (M)	374 ± 30[d]		Mount Sylvester

[a]M = magmatic phase, H = hydrothermal phase
[b]Ages determined for the adjacent Koskaecodde and Mollyguajeck plutons not considered here
[c]No sample or analytical details reported
[d]Recalculated using ^{87}Rb decay constant = 1.42 x 10^{-11} yr^{-1} (Steiger and Jager 1977) from original ages
[e]Originally reported age using ^{87}Rb decay constant = 1.47 x $10^{-11}$$yr^{-1}$

discrete lithological units or *facies*, based on their ages, petrology and geochemistry, but the boundaries between these are commonly gradational or unexposed. Initially, Dickson (1983) proposed nine numbered lithological units (including three subunits) for the batholith. This classification was subsequently modified by later workers to 10 numbered units (*e.g.*, Tuach *et al.*, 1986) and eventually to seven named units (Tuach and Kontak, 1986; Tuach, 1987). Some areas originally included within the Ackley Granite are now excluded based on geochronological evidence that shows them to be some 20 Ma older. The current extent of the batholith is shown in Figure 1.

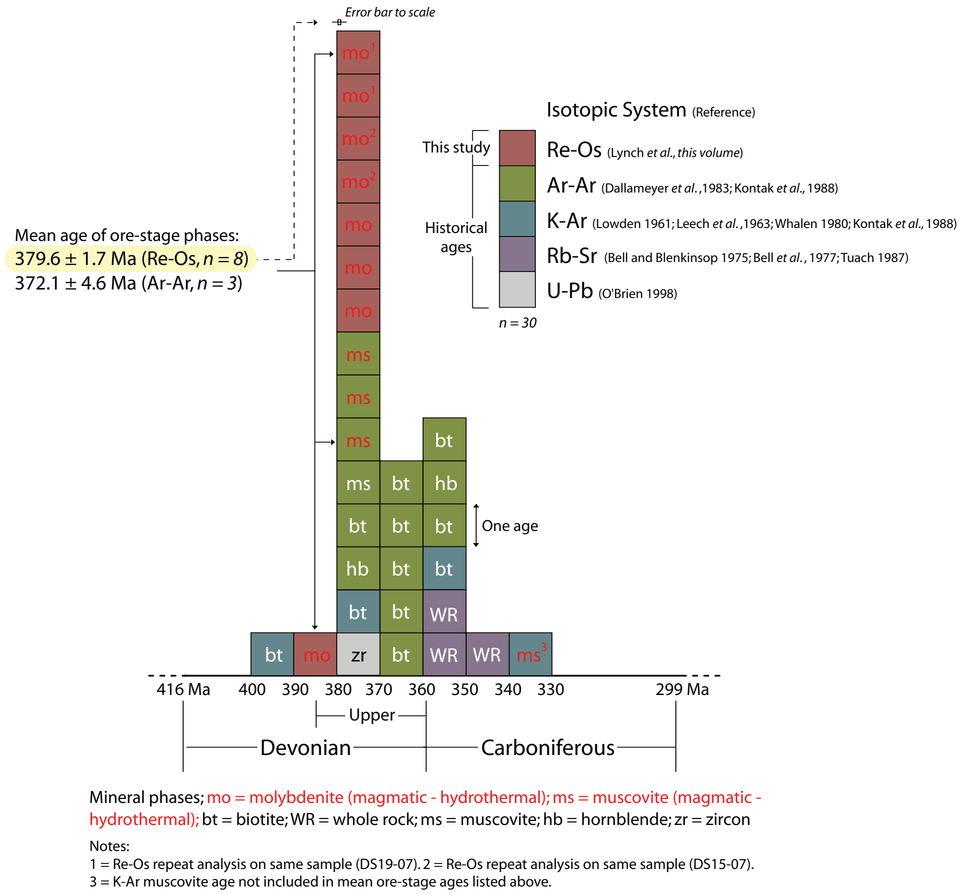

Figure 2. *Histogram showing the age determinations from previous studies and those from this investigation;* see *text for discussion. Geological time scale based on Gradstein* et al. *(2004).*

The batholith is divided into two broad lithological groups. The dominant rock type north and west of the Dover–Hermitage Bay Fault is a medium- to coarse-grained, K-feldspar-porphyritic, biotite granite containing rare muscovite (Kepenkeck and Mount Sylvester units) that has intruded the Cambro-Ordovician metasedimentary rocks of the Gander Zone (*see* Valverde-V Aquerod *et al.*, 2005). To the south and east of the fault, the main rock types can be summarized as a medium- to coarse-grained, equigranular to K-feldspar-porphyritic, biotite granite (Meta, Tolt, Hungry Grove, Sage Pond and Rencontre Lake units) containing localized areas of aplitic and pegmatitic phases (*e.g.*, Rencontre Lake unit). These rocks intrude late Precambrian volcanic and sedimentary rocks, as well as late Precambrian rocks of the Cross Hills Plutonic Suite. Along the southern contact, the batholith is predominantly in contact with rhyolites of the late Precambrian Belle Bay Formation, with grain size in the granite generally decreasing toward the contact. Geochemically, the batholith shows systematic spatial variations in both major- and trace-element distributions (Whalen, 1983; Tuach *et al.*, 1986, 1988). These elemental distributions show that magmatic fractionation increases toward the granite's mineralized southeast and southwest contacts. This Mo and Sn–W mineralized area is thought to represent a highly evolved, shallow, roof-zone where volatile enrichment, transportation and deposition, driven by convective magmatic processes, produced mineralization and variable alteration from a residual melt (Whalen, 1980, 1983; Tuach *et al.*, 1986).

Disseminated molybdenite mineralization occurs at three main locations at, or near, the southern contact of the Ackley Granite, which are known as Ackley City, Wyllie Hill and Motu (Figure 1). The mineralization at these three sites is broadly similar, although Wyllie Hill differs from the other prospects in having a greater concentration of other sulphide minerals, notably pyrite and chalcopyrite. The mineralization is described in detail by White (1940) and Whalen (1980), and is reviewed and illustrated by Kerr *et al.* (*this volume*).

PREVIOUS GEOCHRONOLOGICAL STUDIES

Several previous geochronological studies, employing a variety of radiometric techniques, have been carried out on the Ackley Granite (Table 1, Figures 1 and 2). The earliest ages showed considerable variation and large uncertainties. For example, recalculated K–Ar data for magmatic biotite provided ages of 374 ± 30 Ma (Lowden, 1961) and 399 ± 32 Ma (Leech *et al.*, 1963) for geographically opposing ends of the pluton (Kepenkeck and Tolt facies, respectively). The interpretation of these ages proposed that granite emplacement was a protracted, polyphase magmatic event. More consistent Rb–Sr whole-rock isochron ages of 345 ± 10 Ma (Bell and Blenkinsop, 1975) and 345 ± 5 Ma (Bell *et al.*, 1977) were subsequently obtained for the emplacement of the entire batholith. Recalculation of these ages, using a revised ^{87}Rb decay constant, suggested an emplacement age of ca. 355 Ma (± 5 Ma in Tuach (1987), ± 10 Ma in Kontak *et al.*, (1988)). An additional Rb–Sr study reported a 10-point isochron age of 353 ± 9 Ma, which is consistent with the previous Rb–Sr data (Tuach, 1987).

The results of more recent geochronology have indicated that the timing of Ackley Granite emplacement and associated mineralization predominantly occurred during Upper Devonian times. Kontak *et al.* (1988) comprehensively dated the granite using the Ar–Ar and K–Ar chronometers. This study found that the main phase of plutonism occurred between 378 and 367 Ma (± 6 Ma) suggesting an episodic emplacement of six intrusive units along an approximately north-south lineament. Hydrothermal muscovite Ar–Ar plateau ages from the mineralized Rencontre Lake and Sage Pond areas indicated granophile mineralization occurred between ca. 374 and 371 Ma (± 5 Ma), coincident with the main phase of plutonism. These ages contrast with a much younger estimate of 338 ± 7 Ma, based on K–Ar data from muscovite in associated greisens (Whalen, 1980). Furthermore, the hydrothermal muscovite Ar–Ar dates are older than the calculated ages of magmatic minerals for the same parts of the pluton, although the dates are in agreement when considering the upper and lower uncertainties. A single K–Ar biotite age of 352 ± 5 Ma was determined from the southeastern Tolt facies (Kontak *et al.*, *op. cit.*). This date is concordant with previously calculated Ar–Ar biotite and hornblende data by Dallmeyer *et al.* (1983), indicating emplacement of the Tolt facies occurred at ca. 355 ± 10 Ma (Figure 1). Thus, the combined Ar–Ar and K–Ar ages apparently identify a secondary younger magmatic event that resulted in the intrusion of the granite's southeastern lobe, and suggest Ackley-related plutonism may have continued into the Early Carboniferous.

A single U–Pb zircon age determination of 377 ± 3 Ma tentatively appeared on a medium-scale (1:100 000) geological map of the Connaigre Peninsula, incorporating the southwestern portion of the Ackley Granite (O'Brien, 1998). The sample location, believed to be at the northern end of Long Harbour, falls within the Hungry Grove unit of the granite. This age provides an additional constraint on the timing of Ackley Granite crystallization; however, no details about the sample or the analytical methods used have been published to date.

Re–Os GEOCHRONOLOGY

SAMPLING AND ANALYTICAL PROCEDURES

Mineralized host-rock and vein material were collected during reconnaissance field sampling in the fall of 2007. Sampling was restricted to Mo-bearing prospects in the Rencontre Lake and Sage Pond units along the southern margin of the Ackley Granite (Figure 1). Here, we describe initial work carried out on samples obtained from three localities visited in the Rencontre Lake unit only; Motu, Ackley City and Wylie Hill (Table 2).

Six molybdenite separates were obtained using a combination of rock crushing (shatter-box with porcelain disk mill), magnetic separation (Frantz Isodynamic separator), heavy liquid separation (LST) and water floatation (MilliQ). A uniform grain size of between 74 µm and 210 µm was achieved by mesh sieving during the separation process. Molybdenite was separated from variably altered to fresh granitic whole rock from all three localities (Motu, Ackley City and Wylie Hill) and quartz ± muscovite veins at one locality (Ackley City). The Carius tube method was used for the dissolution of molybdenite and equilibration of sample and tracer Re and Os (*e.g.*, Creaser *et al.*, 1993; Shirey and Walker, 1995). The weight of each molybdenite sample used during the analysis was approximately 100 mg (Table 3). Sample molybdenite was dissolved and equilibrated with a known amount of ^{185}Re and isotopically normal Os in inverse aqua-regia (2:1, 16 *N* HNO_3:12 *N* HCl, 3 ml) at 240°C for a 24-hour period. Solvent extraction and microdistillation was used to isolate Os, while anion exchange chromatography was used to isolate Re (*cf.* Selby and Creaser, 2001a).

The concentrations of ^{187}Re and ^{187}Os were determined at the Northern Centre for Isotopic and Elemental Tracing facility, Durham University, using isotope dilution–thermal ionization mass spectrometry (ID-TIMS). Isolated and purified Re and Os solutions were loaded onto Ni and Pt filaments, respectively, for analysis by a Thermo Finnigan TRITON mass-spectrometer using Faraday collectors. Rhenium and osmium concentrations and Re–Os ages are calculated using uncertainties in Re and Os mass-spectrometer measurements, spike and standard Re and Os isotopic compositions, calibration uncertainties of ^{185}Re and ^{187}Os and weighing uncertainties. Ages are calculated using the decay constant $^{187}Re = 1.666 \times 10^{-11}\ yr^{-1}$ of Smoliar *et al.* (1996). An international laboratory reference material (NIST certified, RM Henderson (H2A), Markey *et al.*, 2007, Table 3) of ultra-fine molybdenite powder from the Henderson Mine,

Table 2. Location and geological description of samples selected for Re–Os geochronology

Sample no.	Easting[a]	Northing[a]	Ackley Granite Facies	Description	Essential Mineralogy[b]
Motu Showing					
DS17-07	632644	5283208	Rencontre Lake	Molybdenite occurs as disseminated 1 - 15mm anhedral to subhedral,- miarole filling knots and rosettes in pink, quartz-phyric, aplitic K-feldspar granite	Ksp-Qtz-Pl-Bt-Mo-Hem±Ms
Ackley City Prospect					
DS13-07	634569	5283576	Rencontre Lake	Molybdenite occurs as disseminated 2 - 20 mm anhedral grains and subhedral rosettes in pinkish red K-feldspar granite	Ksp-Qtz-Pl-Bt-Mo-Ms±F±Cp
DS14-07	634569	5283576	Rencontre Lake	Molybdenite occurs as stringer anhedral flakes in quartz veins with associated greisen in pinkish red K-feldspar granite	Ksp-Qtz-Pl-Bt-Mo-Ms
DS15-07	634569	5283576	Rencontre Lake	Molybdenite occurs as anhedral flakes with associated greisen in a pinkish red K-feldspar granite	Ksp-Qtz-Pl-Bt-Mo-Ms
DS16-07	634569	5283576	Rencontre Lake	Molybdenite occurs as fine grained anhedral disseminations along fracture surfaces in pinkish red pegmatitic K-feldspar granite	Ksp-Qtz-Pl-Bt-Mo
Wyley Hill Prospect					
DS19-07	638176	5286364	Rencontre Lake	Molybdenite occurs as 1 - 4 mm anhedral disseminations associated with circular pyrite-limonite staining in pale pink, aplitic K-feldspar granite	Ksp-Qtz-Pl-Bt-Py-Mo-Lim±Cp

[a] UTM NAD27 Zone 21T/U Cartesian coordinate
[b] Qtz: quartz, Pl: plagioclase, Ksp: K-feldspar, Bt: biotite, Ms: muscovite, Py: pyrite, Cp: chalcopyrite, Mo: molybdenite, F: fluorite, Hem: hematite, Lim: limonite

Colorado, USA, was analyzed to maintain quality standards and assess inter-laboratory reproducibility. For this control a Re–Os age of 27.50 ± 0.11 Ma (n = 1, 2σ, 0.4%) was determined (Table 3). This date is slightly younger (0.6%) than the control samples certified model age of 27.656 ± 0.022 Ma (n = 20).

RESULTS

Rhenium and osmium ages were determined for disseminated molybdenite at the Motu (DS17-07), Ackley City (DS13-07, DS15-07, DS16-07) and Wylie Hill (DS19-07) showings and vein-hosted molybdenite from Ackley City (DS14-07; Table 3). Samples DS15-07 from Ackley City and DS19-07 from Wylie Hill were analyzed in duplicate (Table 3). The results of Re–Os geochronology for a total of six samples are presented in Table 3. The Re and ^{187}Os abundances range from 2.64 to 28.25 ppm, and 10.60 to 112.82 ppb, respectively. The calculated ages range from 377.5 ± 1.6 Ma to 381.8 ± 1.8 Ma. At the Motu showing, a single Re–Os age indicates that molybdenite formed at 378.1 ± 1.7 Ma (2σ, 0.4%). Two Re–Os molybdenite ages from the Wylie Hill prospect signify mineralization occurred earlier at 380.2 ± 1.6 Ma (n = 2, 2σ, 0.4%). Four Re–Os ages from the Ackley City prospect, centrally positioned between Motu and Wylie Hill, indicate disseminated mineralization occurred at 381.8 ± 1.8 Ma, 380.1 ± 1.6 Ma, 379.6 ± 1.7 Ma (2σ, 0.4%) and 377.9 ± 1.7 Ma (n = 2, 2σ, 0.4%; Table 3). In addition, molybdenite associated with quartz veins, knots and pods formed at 379.6 ± 1.7 Ma (2σ, 0.4%). All of the Re–Os molybdenite dates in the Ackley Granite overlap within uncertainty.

Table 3. Re–Os isotope data for molybdenite from mineralization in the SW sector of the Ackley Granite

Sample no.	Sample weight (g)	Total Re (ppm)	^{187}Re(ppm)	^{187}Os(ppb)	Re-Os age (Ma)
Motu Showing					
DS17-07	0.100	5.53 ± 0.02	3.48 ± 0.01	21.98 ± 0.06	378.1 ± 1.7
Ackley City Prospect					
DS13-07	0.100	6.78 ± 0.02	4.26 ± 0.01	27.06 ± 0.07	380.1 ± 1.6
DS14-07	0.100	3.02 ± 0.01	1.90 ± 0.01	12.02 ± 0.03	379.6 ± 1.7
DS15-07	0.103	3.19 ± 0.01	2.00 ± 0.01	12.67 ± 0.04	378.2 ± 1.7
DS15-07[a]	0.101	3.18 ± 0.01	2.00 ± 0.01	12.63 ± 0.03	377.5 ± 1.6
DS16-07	0.100	2.64 ± 0.01	1.66 ± 0.01	10.60 ± 0.03	381.8 ± 1.8
Wyley Hill Prospect					
DS19-07	0.102	26.65 ± 0.09	16.75 ± 0.06	106.40 ± 0.27	380.1 ± 1.6
DS19-07[a]	0.020	28.25 ± 0.11	17.75 ± 0.07	112.82 ± 0.36	380.2 ± 1.6
Reference Material					
H2A[b]	0.101	11.10 ± 0.04	6.98 ± 0.02	3.20 ± 0.01	27.50 ± 0.11

Notes: All uncertainties are at the 2σ level; age calculated using the decay constant λ^{187}Re = 1.666 x 10^{-11} yr^{-1} (Smoliar *et al.,* 1996)

[a]Duplicate sample

[b]Henderson molybdenite reference material (Markey *et al.* 2007)

DISCUSSION AND CONCLUSIONS

The Re–Os results, taking into account the reported uncertainties of the determined ages, indicate that the three molybdenite prospects in the southwestern Ackley Granite formed penecontemporaneously at *ca.* 380 Ma. The hydrothermal muscovite ages obtained from the Rencontre Lake area (Kontak *et al.*, 1988; Table 1) are younger than the Re–Os dates, and only broadly overlap within uncertainty. The Ar–Ar and Re–Os dates are in better agreement when the Ar–Ar dates are corrected by 0.65% (a correction needed to align U–Pb and Ar–Ar ages; Kuiper *et al.*, 2008). However, the Ar–Ar ages remain slightly younger than the Re–Os ages (Figures 1 and 2). This likely reflects the lower closure temperature (~ 350°C) of the Ar–Ar system in micas, compared to that of Re–Os molybdenite systematics (Selby and Creaser, 2001a). Given that molybdenite mineralization in the Ackley Granite is considered to be syngenetic in origin (*e.g.*, Whalen, 1980; Kerr *et al.*, *this volume*), the Re–Os ages provide the best estimate of the crystallization age of the pluton (*cf.* Selby *et al.*, 2007). The new Re–Os dates indicate a Late Devonian (Frasnian) age for granite crystallization and coeval sulphide mineralization. This estimate is consistent with emplacement ages obtained for other Late Devonian granites in Newfoundland using U–Pb ID–TIMS methods; for example, the Francois Granite (378 ± 2 Ma) and the St. Lawrence Granite (374 ± 2 Ma; Kerr *et al.*, 1993). The Re–Os molybdenite ages also compare favourably with the only U–Pb zircon age reported for the Ackley Granite (377 ± 3 Ma; O'Brien, 1998). Given that the Ackley Granite is considered to be composite in nature, the ages do not necessarily indicate that all its constituent units were emplaced at the same time (Figure 1). Future results from other molybdenite-bearing localities in the Sage Pond area will be of interest in this context. The precise and very consistent information obtained from these initial results suggests that the Re–Os method has excellent promise for constraining the timing of late magmatism and associated mineralization in Newfoundland, and linking such events to those recognized elsewhere in the Appalachian–Caledonian Orogen (*e.g.*, Feely *et al.*, 2007).

These results are part of a broader regional study that aims to gain a better understanding into the nature and timing of granophile mineralization in Newfoundland. Granitoid-related, porphyry-type copper and molybdenite deposits have long been recognized from several localities along eastern Canada's Appalachian corridor (Hollister *et al.*, 1974), but these are not as well understood as the younger deposits in the Cordillera. Application of a suite of geochemical tools (geochronology, fluid inclusions, stable isotopes) should lead to a better understanding of this type of mineralization occurring within an older and more deeply eroded mountain belt. Future research will also facilitate correlations between Ireland, Britain and Newfoundland in terms of granite emplacement and associated mineralization.

ACKNOWLEDGMENTS

The authors acknowledge and thank the following individuals and organizations. Andy Kerr, for assistance with logistics and field sampling, his encouragement for the project and his constructive review. James Conliffe, for his assistance during field sampling. Callum Thomson and Alice Rogers are thanked for their help during sample preparation and analysis. Gary Lewis, Alterra Resources and Nidon Enterprises are thanked for permission to access the prospects. Research work reported here is supported by a postgraduate fellowship from the Irish Research Council for Science, Engineering and Technology (IRCSET). Additional financial support has been provided by the Ireland–Newfoundland Partnership (INP), an inter-governmental body that encourages collaborative social, cultural and scientific studies between the two islands. Edward Lynch also acknowledges support from a student research fellowship provided by the Society of Economic Geologists (SEG).

REFERENCES

Bell, K. and Blenkinsop, J.
1975: The geochronology of eastern Newfoundland. Nature, Volume 254, pages 410-411.

Bell, K., Blenkinsop, J. and Strong, D.F.
1977: The geochronology of some granitic bodies from eastern Newfoundland and its bearing on Appalachian evolution. Canadian Journal of Earth Sciences, Volume 14, pages 456-476.

Bingen, B., Stein, H.J., Bogaerts, M., Bolle, O. and Mansfeld, J.
2006: Molybdenite Re-Os dating constrains gravitational collapse of the Sveconorwegian orogen, SW Scandinavia. Lithos, Volume 87, pages 328-346.

Colman-Sadd, S.P., Hayes, J.P. and Knight, I.
1990: Geology of the island of Newfoundland. Newfoundland Department of Mines and Energy, Geological Survey Branch, Map 90-01.

Creaser, R.A., Papanastassiou, D.A. and Wasserburg, G.J.
1993: Rhenium-osmium isotope systematics of group IIA and group IVA iron meteorites. Geological Association of Canada-Mineralogical Association of Canada Annual Meeting, Edmonton, Abstracts, page A20.

Dallmeyer, R.D., Hussey, E.M., O'Brien, S.J. and O'Driscoll, C.F.
1983: Chronology of tectonothermal activity in the western Avalon Zone of the Newfoundland Appalachians. Canadian Journal of Earth Sciences, Volume 14, pages 456-476.

Dickson, W.L.
1983: Geology, geochemistry and mineral potential of the Ackley Granite and parts of the Northwest Brook and Eastern Meelpaeg complexes, southeast Newfoundland. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 83-6, 129 pages.

Feely, M., Selby, D., Conliffe, J. and Judge, M.
2007: Re-Os geochronology and fluid inclusion microthermometry of molybdenite mineralization in the late-Caledonian Omey Granite, western Ireland. Applied Earth Sciences (Trans. Inst. Min. Metall. B), Volume 116, pages 143-149.

Gradstein, F.M., Ogg, J.G., Smith, A.G. and 37 others.
2004: A geologic timescale 2004. Cambridge University Press, Cambridge, 589 pages.

Hirt, W., Herr, W. and Hoffmeister, W.
1963: Age determinations by rhenium-osmium method: Radiometric dating. International Atomic Energy Agency, pages 35-43.

Hollister, V.F., Potter, R.R. and Barker, A.L.
1974: Porphyry-type deposits of the Appalachian Orogen. Economic Geology, Volume 69, pages 618-630.

Kerr , A., Dunning, G.R. and Tucker, R.D.
1993: The youngest Paleozoic plutonism of the Newfoundland Appalachians: U-Pb ages from the St. Lawrence and Francois granites. Canadian Journal of Earth Sciences, Volume 30, pages 2328-2333.

Kerr, A., van Nostrand, T., Dickson, L. and Lynch, E.P.
This volume: Molybdenum and tungsten in Newfoundland: A geological overview and a summary of recent exploration developments.

Kontak, D.J., Tuach, J., Strong, D.F., O'Brien, S.J. and Papezik, V.S.
1988: Plutonic and hydrothermal events in the Ackley Granite, southeast Newfoundland, as indicated by total fusion $^{40}Ar/^{39}Ar$ geochronology. Canadian Journal of Earth Sciences, Volume 25, pages 1151-1160.

Kuiper, K.F., Deino, A., Hilgen, F.J., Krijgsman, W., Renne, P.R. and Wijbrans, J.R.
2008: Synchronizing rock clocks of Earth history. Science, Volume 320, pages 500-504.

Leech, G.B., Lowdon, J.A., Stockwell, C.H. and Wanless, R.K.
1963: Age determinations and geological studies

(including isotopic ages - Report 4). Geological Survey of Canada, Paper 63-17, 121 pages.

Lowden, J.A.
1961: Age determinations by the Geological Survey of Canada, Report 2, Isotope Ages. Geological Survey of Canada, Paper 61-17, 85 pages.

Mao, J.W., Xie, G.Q., Bierlein, F., Qu, W.J., Du, A.D, Ye, H.S., Pirajno, F., Li, H.M., Guo, Y.F. and Yang, Z.Q.
2008: Tectonic implications from Re-Os dating of Mesozoic molybdenum deposits in the East Quinling-Dabie orogenic belt. Geochimica et Cosmochimica Acta, Volume 72, pages 4607-4626.

Markey, R., Stein, H.J., Hannah, J.L., Zimmerman, A., Selby, D. and Creaser, R.A.
2007: Standardizing Re-Os geochronology: a new molybdenite reference material (Henderson, USA) and the stoichiometry of Os salts. Chemical Geology, Volume 244, pages 74-87.

O'Brien, S.J., Nunn, G.A.G., Dickson, W.L. and Tuach, J.
1984: Geology of the Terrenceville (1M/10) and Gisborne Lake (1M/15) map areas, southeast Newfoundland. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 84-4, 54 pages.

O'Brien, S.J. (compiler).
1998: Geology of the Connaigre Peninsula and adjacent areas, southern Newfoundland. Geological Survey, Department of Mines and Energy, Map 98-02, Open File Map NFLD/2660.

Selby, D. and Creaser, R.A.
2001a: Re-Os geochronology and systematics in molybdenite from the Endako porphyry molybdenum deposit, British Columbia, Canada. Economic Geology, Volume 96, pages 197-204.

2001b: Late and mid-Cretaceous mineralization in the northern Canadian Cordillera: Constraints from Re-Os molybdenite dates. Economic Geology, Volume 96, pages 1461-1467.

2004: Macroscale NTIMS and microscale LA-MC-ICP-MS Re-Os isotopic analysis of molybdenite: testing spatial restriction for reliable Re-Os age determinations, and implications for the decoupling of Re and Os within molybdenite. Geochimica et Cosmochimica Acta, Volume 68, pages 3897-3908.

Selby, D., Creaser, R.A., Stein, H.J., Markey, R.J. and Hannah, J.L.
2007: Assessment of the ^{187}Re decay constant by cross-calibration of Re-Os molybdenite and U-Pb zircon chronometers in magmatic ore systems. Geochimica et Cosmochimica Acta, Volume 71, pages 1999-2013.

Shirey, S.B. and Walker, R.J.
1995: Carius tube digestion for low-blank rhenium-osmium analysis. Analytical Chemistry, Volume 67, pages 2136-2141.

Smoliar, M.I., Walker, R.J. and Morgan, J.W.
1996: Re-Os isotope constraints on the age of Group IIA, IIIA, IVA and IVB iron meteorites. Science, Volume 271, pages 1099-1102.

Steiger, R.H. and Jager, E.
1977: Subcommission on geochronology: Convention on the use of decay constants in geo- and cosmochronology. Earth and Planetary Science Letters, Volume 36, pages 359 - 362.

Stein, H.J., Markey, R.J., Morgan, J.W., Du, A. and Sun, Y.
1997: Highly precise and accurate Re-Os ages for molybdenite from the East Qinling molybdenum belt, Shaanxi province, China: Economic Geology, Volume 92, pages 827-835.

Stein, H.J., Markey, R.J., Morgan, J.W., Hannah, J.L. and Schersten, A.
2001: The remarkable Re-Os chronometer in molybdenite: how and why it works. Terra Nova, Volume 13, pages 479-486.

Stein, H.J., Morgan, J.W., Markey, R.J. and Hannah, J.L.
1998: An introduction to Re-Os: What's in it for the mineral industry? SEG Newsletter, Volume 32 (1), pages 8-15.

Stein, H.J., Scherstén, A., Hannah, J. and Markey, R.
2003: Sub-grain scale decoupling of Re and ^{187}Os and assessment of laser ablation ICP-MS spot dating in molybdenite. Geochimica et Cosmochimica Acta, Volume 67, pages 3673-3686.

Tuach, J.
1987: The Ackley high-silica magmatic/metallogenic system and associated post-tectonic granites, southeast Newfoundland. Unpublished PhD thesis, Memorial University of Newfoundland, St. John's, Newfoundland, 455 pages.

Tuach, J., Davenport, P.H., Dickson, W.L. and Strong, D.F.
1986: Geochemical trends in the Ackley Granite, southeast Newfoundland: their relevance to magmatic-metallogenic processes in high-silica granitoid systems.

Canadian Journal of Earth Sciences, Volume 23, pages 747-765.

Tuach, J., Kerrich, R., Willmore, L.M. and Strong, D.F.
1988: Source terranes, magmatic evolution and hydrothermal regimes in the Mo-, Sn-mineralized Ackley Granite, Newfoundland: evidence from combined geochemical and oxygen isotope data. *In* Recent Advances in the Geology of Granite-related Mineral Deposits. *Edited by* R.P. Taylor and D.F. Strong. Bulletin, Canadian Institute of Mining and Metallurgy, pages 342-350.

Tuach, J. and Kontak, D J.
1986: Rb-Sr and $^{40}Ar/^{39}Ar$ studies and redefinition of the Ackley Granite, southeast Newfoundland. Annual Spring Meeting. Newfoundland Section of the Geological Association of Canada. Program with abstracts, page 9.

Valverde-V Aquerod, P., Van Staal, C.R., McNicoll, V. and Dunning, G.R.
2005: Mid – Late Ordovician magmatism and metamorphism along the Gander margin in central Newfoundland. Journal of the Geological Society of London, Volume 162, pages 1-16.

Whalen, J.B.
1976: Geology and geochemistry of molybdenite showings of the Ackley Granite, Fortune Bay, Newfoundland. Unpublished M.Sc. thesis, Memorial University of Newfoundland, St. John's, Newfoundland, 267 pages.

1980: Geology and geochemistry of the molybdenite showings of the Ackley City batholith, southeast Newfoundland. Canadian Journal of Earth Sciences, Volume 17, pages 1248-1258.

1983: The Ackley City batholith, southeastern Newfoundland: Evidence for crystal versus liquid-state fractionation. Geochimica Cosmochimica Acta Volume 47, pages 1443-1457.

White, D.E.
1940: The molybdenite deposits of the Rencontre East area, Newfoundland. Economic Geology, Volume 35, No. 8, pages 967-995.

Williams, H.
1979: Appalachian Orogen in Canada. Canadian Journal of Earth Sciences, Volume 16, pages 792-807.