THE TIMING OF GOLD MINERALIZATION ON THE BAIE VERTE PENINSULA: PROGRESS REPORT ON Re–Os PYRITE GEOCHRONOLOGY

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ABSTRACT

The Re–Os geochronometer provides a direct dating method for epigenetic gold deposits, if it can be applied to sulphides, such as pyrite or arsenopyrite, which are commonly associated with gold. This article documents the application of this method to gold deposits on the Baie Verte Peninsula. Pyrites from the Stog'er Tight and Pine Cove gold deposits are low-level highly radiogenic (LLHR) sulphides, amenable to Re–Os model-age calculations. These data indicate ages of 411 ± 7 Ma and 420 ± 7 Ma, respectively. In the case of Stog'er Tight, results are in agreement with previous U–Pb ages from 'hydrothermal' zircons in alteration assemblages. The overlap suggests that both deposits likely formed at approximately the same time. However, Re–Os data from the Nugget Pond gold deposit are problematic, as some samples have significant amounts of common Os, and others yield model ages of 549 to 511 Ma, which are older than the inferred age of the host rocks. The Re–Os data are also inconsistent with a previous U–Pb age of ca. *374 Ma obtained from a crosscutting sulphide-bearing vein. These enigmatic results may reflect the incorporation of older Re-rich syngenetic (sedimentary) sulphides, followed by net loss of Re during later epigenetic gold mineralization. Further investigation of this problem is warranted, because interaction between hydrothermal fluids and pre-existing sulphides is known to be an important metallogenic process in other settings. Results suggest that the Re–Os method has good potential to better constrain the timing of gold mineralization in Newfoundland, providing that the associated sulphides contain sufficient Re to generate measurable radiogenic Os.*

INTRODUCTION

Knowledge of the timing of mineralization is important in developing genetic models for ore deposits, which are used to assess the potential of specific geological units or structures, and prioritize their exploration. Age constraints for syngenetic mineralization are readily obtained from stratigraphic and/or geochronological studies of the host rocks. However, such information is difficult to obtain for epigenetic styles of mineralization, such as most gold deposits. Several approaches to this problem are possible, but these generally do not provide direct information. Radiometric ages from pre- and post-mineralization units (*e.g.*, dykes) may provide tight constraints (*e.g.*, Kerr and van Breemen, 2007). More commonly, however, these relative age constraints are so broad as to be useless. Dates from phyllosilicate alteration assemblages using K–Ar or Ar–Ar methods (*e.g.*, Pettke *et al.*, 1999) rely upon potentially subjective links between mineralization and alteration and, moreover, may be disturbed by later events. Mineralized veins and replacement deposits may contain minerals suitable for U–Pb geochronology, such as zircon, rutile, titanite or monazite (*e.g.*, Lin and Corfu, 2002; Ramezani *et al.*, 2002), but this is certainly not the norm. The gangue minerals that are directly associated with epigenetic gold mineralization are typically quartz, carbonates and sulphides, none of which are amenable to dating through common geochronological methods. However, the Re–Os geochronometer can provide direct age information from sulphides, because these siderophile and chalcophile platinum-group elements (PGE) are incorporated into these minerals in miniscule amounts, typically measured in parts-per-billion (ppb) or even parts-per-trillion (ppt). The Re–Os geochronometer is best known through its use to date molybdenites, but it has been applied to epigenetic gold mineralization with variable success (*e.g.*, Stein *et al.*, 2000; Arne *et al.*, 2001; Morelli *et al.*, 2005). It is a technique that holds great promise, but it is far from simple, as it requires analytical precision close to the detection limits of modern technology, and there are few precedent studies to guide the interpretation of data.

This article is a progress report on an ongoing project to apply the Re–Os technique to gold mineralization in the

Newfoundland Appalachians. The article summarizes the first precise Re–Os ages from gold deposits in Newfoundland, for which more complete information will be published elsewhere. It also reports some problematic results that illustrate the potential for geological and/or analytical complications in the application of the method.

THE Re–Os GEOCHRONOMETER AND ITS APPLICATION

The Re–Os geochronometer is based on the decay of the isotope ^{187}Re to ^{187}Os. The half-life of ^{187}Re is very long (approximately 42 Ga), so the amount of radiogenic ^{187}Os that exists in nature is trivial. Both Re and Os are rare PGE, with average crustal abundances of a few ppb for Re and <<1 ppb for Os. The most common application of the method is to date molybdenite (MoS_2), which concentrates Re at ppm levels, but contains essentially no common Os. In molybdenite dating, all of the Os measured in the sample is considered radiogenic, and concentration data from single samples yield accurate model ages. The method has been widely used to date granite-related mineralization and related host rocks. The first Re–Os ages on molybdenite prospects in Newfoundland, hosted by the Ackley Granite, were recently reported by Lynch *et al.* (2009).

Rhenium and osmium are siderophile and chalcophile trace elements that have a strong affinity for sulphides, and common sulphide minerals such as pyrite, arsenopyrite, bornite and chalcopyrite can also provide age information. The method has been applied to orthomagmatic sulphide deposits, which are commonly enriched in PGE. However, because Re and Os are both incorporated into sulphides, such age determinations require use of the traditional isochron method, in which the isotope ^{188}Os serves as the common denominator; ^{187}Os/^{188}Os is regressed against ^{187}Re/^{188}Os. Isochron determinations also yield the initial ^{187}Os/^{188}Os of the sample, which is a valuable isotopic tracer. A local example of this application is the 1323 ± 135 Ma Re–Os isochron obtained by Lambert *et al.* (1999) from the Voisey's Bay deposit in Labrador. In this case, the sulphide-rich samples contained >100 ppb Re, and the amounts of Os were (relatively speaking) extremely high (generally >10 ppb). However, the accuracy of this particular result was compromised by limited variation in Re/Os ratio in the sulphides, which is a common problem in magmatic sulphide systems, where such ratios are strongly controlled by partition coefficients and the magma to sulphide liquid mass ratio (*e.g.*, Campbell and Naldrett, 1975).

Rhenium–osmium studies of sulphides from other environments, such as gold deposits, are inherently more difficult, because sulphides in these environments typically contain mere traces of Re (tens of ppb Re, at most) and Os concentrations are typically measured in parts per trillion. Isotopic analysis at such low concentrations is a technical challenge, and uncertainties due to blank corrections become significant. If common Os is also present in the samples, interpretation of results may be problematic. Geochronological studies of Re-depleted sulphides may be imprecise, and thus of limited value. This problem was encountered in an initial attempt to date disseminated gold mineralization from White Bay in western Newfoundland. The pyrite separates contained only 0.3 to 1.0 ppb Re, and arsenopyrite separates were devoid of measurable Re (Kerr *et al.*, 2006). The age result obtained (327 ± 58 Ma) was imprecise, and proved inaccurate, because subsequent Ar–Ar studies better constrained the timing of mineralization at *ca.* 413 Ma (Kerr and van Breemen, 2007).

Although sulphide minerals in gold deposits generally contain very low Re concentrations, in many cases the sulphides contained little or no Os at the time of formation; thus, the Os that is detected is almost entirely radiogenic. This does not compensate for the difficulties in measuring low Os concentrations but it does allow the calculation of model ages, as for molybdenites. Such sulphides are termed 'low-level highly radiogenic' (LLHR) sulphides (Stein *et al.*, 2000), and provide the best avenue for precise Re–Os geochronology on gold mineralization in the absence of associated molybdenite. This method was used by Morelli *et al.* (2005), who successfully dated vein-style gold deposits in Nova Scotia using pyrite and arsenopyrite separates.

The arsenopyrite work of Morelli *et al.* (2005) inspired initial attempts to date mineralization in White Bay (Kerr *et al.*, 2006) and then led to the present study. The first choice was to investigate three gold prospects in which arsenopyrite is common, as well as pyrite (Figure 1). These were the Moosehead prospect (near Bishops Falls), the H-Pond prospect (near Gander), and the Huxter Lane prospect (in south-central Newfoundland). All three areas were examined in 2006, and sulphide-rich material was sampled from diamond-drill core. However, initial tests of sulphide separates showed that both pyrite and arsenopyrite were Re-poor (<1 ppb), suggesting that any Re–Os isotopic analyses would be imprecise, and ages would have large uncertainties. Attention was next focused on samples collected from three well-known deposits on the Baie Verte Peninsula, *i.e.*, Nugget Pond, Pine Cove, and Stog'er Tight (Figure 1). These deposits contain little or no arsenopyrite, but all exhibit a strong empirical relationship between gold and pyrite content. Furthermore, existing age constraints for two of these deposits promised independent confirmation of any Re–Os results. Initial test analyses of pyrite separates were more encouraging, suggesting Re contents up to 10 ppb. In total, 13 analyses have now been completed on pyrite separates from these deposits. The Pine Cove and Stog'er Tight
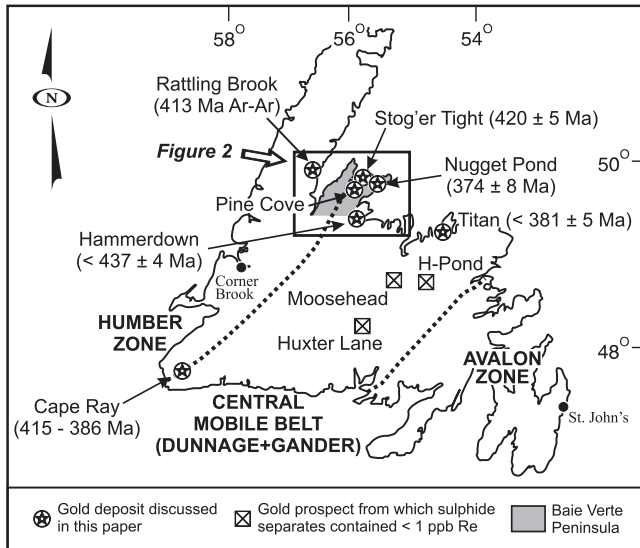
Figure 1. *Location of the Baie Verte Peninsula in Newfoundland, and locations of selected gold deposits, including those for which geochronological information is available. Aside from Rattling Brook, all results indicated are U–Pb determinations, and the sources are indicated in the text. The map also shows the locations of three gold prospects from which test analyses of single sulphide separates indicated low Re contents (<1 ppb), which presently preclude dating.*

pyrites contain little or no common Os (*i.e.*, they are LLHR sulphides) and they provide precise and useful ages. The Nugget Pond pyrites are more variable, in that some contain mostly common Os, whereas others are LLHR sulphides; the data from the latter do permit calculation of model ages, but interpretation of these is problematic.

EXISTING GEOCHRONOLOGICAL CONSTRAINTS ON GOLD MINERALIZATION IN NEWFOUNDLAND

Gold mineralization is scattered across Newfoundland, and there are over 500 individual occurrences (Wardle, 2005). Although the host rocks range in age from late Precambrian to Silurian, the majority of gold showings are hosted by Cambrian and Ordovician volcanic and sedimentary rocks in central Newfoundland. Gold is also present locally in some Silurian volcanic and sedimentary sequences, but is unknown in others. Virtually all gold mineralization in Newfoundland is epigenetic, with the exception of some occurrences in the Avalon Zone that are interpreted to be of epithermal origin, and similar in age to the host rocks. A spatial association between mineralization and prominent late-orogenic fault zones forms the basis for a general view that gold was mobilized and deposited during Silurian and/or Devonian orogenesis (*e.g.*, Tuach *et al.*,

1988; Swinden *et al.*, 2001; Kerr *et al.*, 2005). However, absolute age constraints are available for only a handful of individual gold occurrences.

Existing geochronology suggests that there are at least two periods of Paleozoic gold mineralization in the Newfoundland Appalachians (Figure 1). The older event, corresponding to the Silurian–Devonian boundary, is defined by *ca.* 420 and *ca.* 437 Ma U–Pb zircon dates from the Stog'er Tight and Hammerdown deposits, respectively (Ritcey *et al.*, 1995; Ramezani *et al.*, 2002). The zircons from Stog'er Tight are considered to be part of the hydrothermal alteration assemblage, whereas those at Hammerdown occur in felsic dykes that predate the auriferous veins, and thus provide only a maximum age constraint. The *ca.* 413 Ma Ar–Ar dates from pre- and post-mineralization dykes at the Rattling Brook deposit in White Bay indicate a similar formation age (Kerr and van Breemen, 2007). A second period of mineralization during the Middle to Late Devonian is suggested by an imprecise 374 ± 8 Ma U–Pb xenotime age from quartz–albite–carbonate alteration at the Nugget Pond deposit (R. Parrish, reported by Sangster *et al.*, 2008), and by a *ca.* 381 Ma U–Pb zircon age from altered gabbroic host rocks at the Titan prospect near Gander (McNicoll *et al.*, 2006). The latter age provides only a maximum age constraint, as the dated rock is cut by the mineralized veins.

The same general age pattern is discernable amongst gold deposits in Nova Scotia and New Brunswick (Thorne *et al.*, 2002, and Morelli *et al.*, 2005). However, there are very few geochronological data from any of these areas, and it is thus difficult to assess the reality and significance of such a pattern. Direct Re–Os dating provides a potential method to better understand the temporal framework of gold mineralization and its relationship to tectonic and deformational events.

SUMMARY OF GEOLOGY AND GOLD MINERALIZATION

The Baie Verte Peninsula is well-known for its diverse metallogeny, and also as a critical area in understanding the evolution of the Newfoundland Appalachians. The regional geology of the peninsula was described in detail by Hibbard (1983) and more recent work completed by the Geological Survey of Canada (GSC) is summarized by Castonguay *et al.* (2009) and Skulski *et al.* (2009). The gold deposits that are the subject of this report occur within Early Ordovician volcanic and sedimentary rocks that are assigned to the Snooks Arm Group (Nugget Pond deposit) and the Point Rousse Complex (Stog'er Tight and Pine Cove deposits). The regional geology of the peninsula is illustrated in Figure 2; readers are referred to Hibbard (1983) and other sources (*e.g.*, Skulski *et al.*, 2009) for more detailed information.
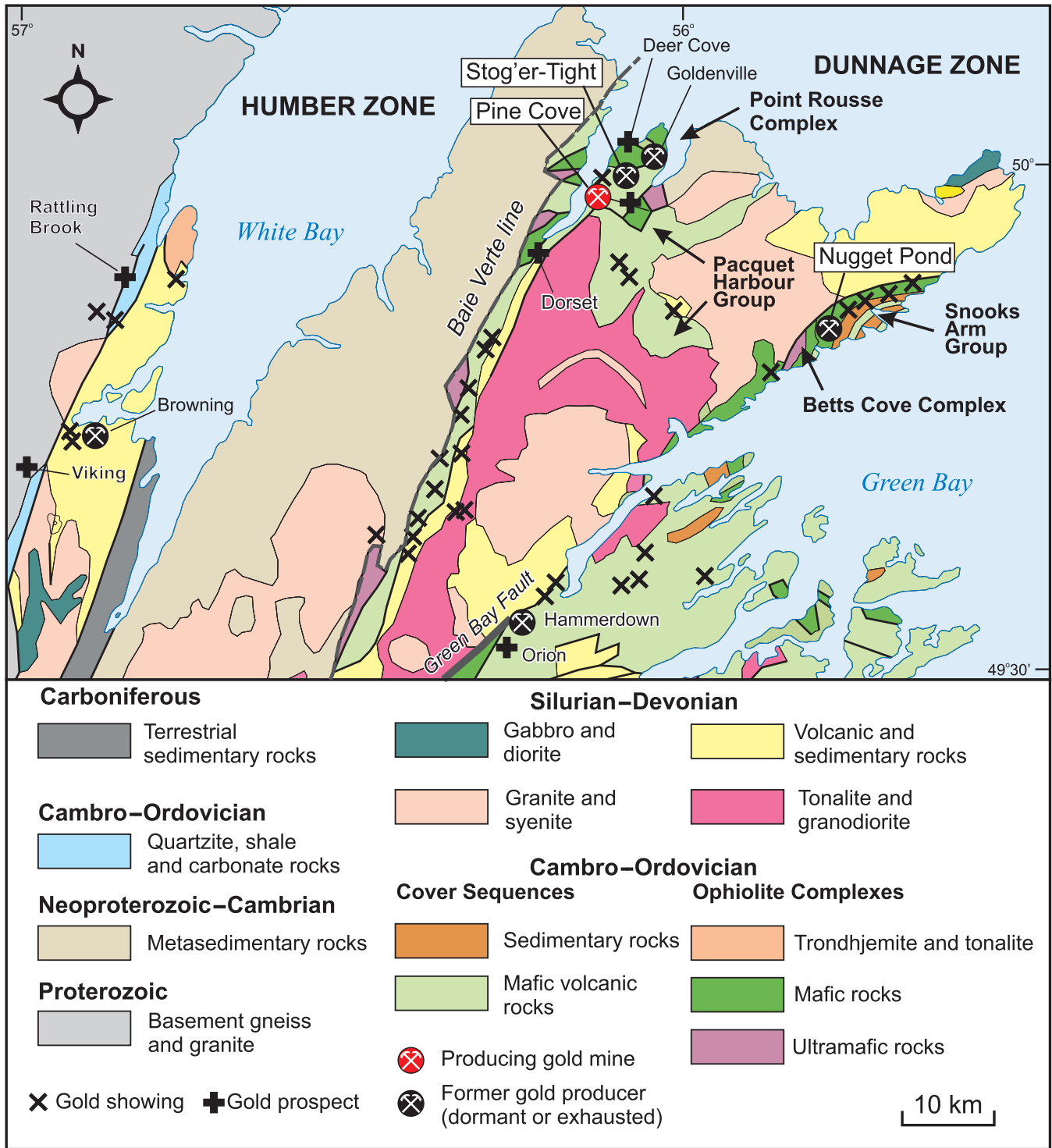
Figure 2. *Simplified geology of the Baie Verte Peninsula and adjacent areas, showing the locations of gold deposits, including present and former producers, prospects and minor showings.*

The locations of the gold deposits investigated as part of this study, as well as other gold prospects and occurrences, are indicated in Figure 2.

The Stog'er Tight gold deposit is hosted within dominantly volcanic rocks of the Point Rousse Complex (Figure 2), and was discovered in the late 1980s. The deposit was

estimated to contain resources of 0.35 Mt at 4.5 g/t Au (Wardle, 2005; MODS data), but attempts to mine it in 1996-97 proved unsuccessful due to a lack of continuity. The deposit is described by Kirkwood and Dubé (1997), Ramezani (2002) and Evans (2001, 2004), from which the following summary is drawn. Evans (2004) classed the deposit in his red albite–ankerite–pyrite replacement subclass. The dominant host to mineralization is a gabbro, which originally formed a sill-like intrusion within mafic volcanic and volcaniclastic rocks. The gabbro was dated imprecisely at 483 +9/-5 Ma using U–Pb methods (Ramezani, 1992), which provides a maximum age for mineralization. The highest grade mineralization is associated with coarse-grained epigenetic pyrite, accompanied by red albite and abundant iron carbonate. Discrete quartz veins are common within the mineralized zones, and the intensity of alteration and mineralization is greatest where veins are abundant. The gold grades are strongly correlated with the amount of sulphide. Gold-bearing quartz veins formed early in the regional deformation sequence (D_1 event of Kirkwood and Dubé, 1992; D_2 event of Castonguay et al., 2009). Zircon in altered mafic rocks at Stog'er Tight was interpreted to be of hydrothermal origin, and gave a U–Pb zircon age of 420 ± 5 Ma (Ramezani et al., 2002).

The Pine Cove gold deposit is also hosted by volcanic rocks of the Point Rousse Complex (Figure 2), and was discovered around the same time as Stog'er Tight. It contains a near-surface resource of almost 3 Mt (Wardle, 2005; MODS data), but has generally low grades (<3 g/t Au). The deposit entered production as a small open-pit operation in early 2008. Evans (2004) classed Pine Cove in his 'carbonate–quartz–sulphide replacement' subclass, and differentiated it from the Stog'er Tight deposit. However, there are similarities between the two deposits. The gold mineralization occurs in mafic volcanic rocks, volcaniclastic sedimentary rocks (typically hematitic) and gabbro. Quartz veins in the deposit are spatially associated with fault zones interpreted as D_2 (likely Silurian) structures by Castonguay et al. (2009). Gold mineralization at Pine Cove is associated with heavily disseminated epigenetic pyrite in altered rocks. The alteration is dominated by chlorite, iron carbonate and white albite; the red albite noted at Stog'er Tight is less common. This replacement-style mineralization is associated with discrete quartz veins and quartz-carbonate breccia zones, which also contain disseminated pyrite. Gold is associated with pyrite, and the grade of mineralization is strongly correlated with the sulphide content. Other than the general correlation of the host rock sequences with units dated at ca. 470 to ca. 465 Ma (Skulski et al., 2009), there are no constraints on the age of mineralization at Pine Cove.

The Nugget Pond gold deposit differs in important respects from Stog'er Tight and Pine Cove. It is hosted mostly by sedimentary rocks at the base of the Snooks Arm Group (ca. 470 Ma; Skulski et al., 2009), and was discovered in 1988. It was brought into production by Richmont Mines in 1997, with a total resource of 0.49 Mt at an impressive grade of 12.3 g/t Au. The underground mine closed in 2002 following exhaustion of the high-grade reserves, although lower grade material remains. The Nugget Pond deposit has a stratiform geometry, in which most mineralization is restricted to a thin sedimentary unit (termed the Nugget Pond horizon) within the mixed sedimentary and volcanic rocks (Swinden et al., 1990; Sangster et al., 2008). The Nugget Pond horizon includes fine-grained greywackes, argillites and both oxide- and sulphide-facies bedded iron formations. The gold mineralization is associated with coarse-grained pyrite, which, in part, overgrows earlier syngenetic or diagenetic pyrite in the host rocks; epigenetic pyrite also overgrows magnetite. Mineralization is spatially associated with veins and pockets of coarse-grained quartz–albite–carbonate rock, which are variably discordant to bedding. This pegmatite-like material locally contains spectacular free gold, but most gold is present as small blebs and inclusions in coarse-grained pyrite. Individual zones within the deposit vary in their details according the exact host rock types, and are discussed in detail by Sangster et al. (2008). The presence of crosscutting quartz–albite-carbonate zones and the localized distribution of alteration suggest that it is an epigenetic replacement-style deposit, rather than a syngenetic accumulation (Swinden et al., 1990; Sangster et al., 2008). Evans (2004) did not discuss Nugget Pond in detail, but grouped similar mineralization at Goldenville (Figure 2) as part of his carbonate–quartz-sulphide replacement class. Importantly, Nugget Pond is the only one of the three studied deposits in which an earlier (syngenetic or diagenetic) generation of pyrite may be present. Xenotime from a quartz–albite–carbonate zone was analyzed by R. Parrish at the GSC, and yielded an age of 374 ± 8 Ma; the data remain unpublished, but the result is quoted by Sangster et al. (2008).

Re–Os GEOCHRONOLOGY

The full details of Re–Os geochronological studies will be presented in a separate publication. The samples used in this study came from several sources and included archived samples collected by A. Kerr, D. Evans and J.L. Smith during field trips, and new sampling at Pine Cove and Stog'er Tight in 2008. The samples were chosen on the basis of pyrite abundance and grain size; the latter being important for hand-picking of pyrite separates. The Nugget Pond ore horizon is not exposed on surface, and the underground workings are now closed; these data thus come entirely from archived samples representing grey-green siltstone and shale containing large pyrite cubes. The exact geographic context of Nugget Pond samples relative to one another is

not known, but all came from the underground stopes, and represent a very distinctive rock type present only in and adjacent to the ore zones.

Sample preparation and isotopic analyses were completed at the University of Durham. Full details of procedures will be presented elsewhere, but the methods correspond in almost all respects to those outlined by Selby *et al.* (2009) in their study of the Ruby Creek copper deposit in Alaska. All ages are calculated using the decay constant for ^{187}Re (1.666×10^{-11} a^{-1}; Smoliar *et al.*, 1996). Data processing and regression analysis were performed using the ISOPLOT program (Ludwig, 2003). The full analytical dataset will be presented elsewhere. The following sections summarize and discuss the preliminary results and their implications.

All of the analyzed pyrite separates had low Re contents, ranging from <1 ppb to about 26 ppb, and only some of the Pine Cove separates contain >10 ppb Re; there are also wide variations in the Re contents of samples from individual deposits. The total Os contents for all separates are also very low, typically 10 to 140 ppt. With the exception of two pyrite separates from Nugget Pond samples, all analyses have extremely high ^{187}Re/^{188}Os (up to 430 000) and ^{187}Os/^{188}Os ratios (up to 3000). Such results indicate that most analyzed samples essentially lack common Os; virtually all contained Os is ^{187}Os, which must be radiogenic. Calculations indicate that all but two separates contain >92% radiogenic Os. These results are definitive of LLHR sulphides, as discussed earlier (*cf.*, Stein *et al.*, 2000; Morelli *et al.*, 2005). The procedures for dealing with these LLHR sulphides differ from those used in conventional isochron calculations, because the data are amenable to model age calculation or simpler regression of daughter (^{187}Os) against parent (^{187}Re) isotope concentrations. It is important to note that model ages from such samples are very different from model ages obtained from other types of isotopic data such as Sm–Nd or Rb–Sr analyses, which have no real geochronological significance. The Sm–Nd or Rb–Sr model ages serve only to indicate the relative antiquity of crustal precursors to samples, and their interpretation is subject to numerous assumptions. In contrast, the only model in Re–Os 'model' ages is simply that the measured ^{187}Os is derived by radioactive decay of ^{187}Re, and this is confirmed by the near-absence of other isotopes of Os in analytical results. The Re–Os model ages thus have direct geochronological meaning. The treatment of LLHR sulphides is essentially the same as that used for calculation of molybdenite ages, aside from the fact that the concentrations of Os are much lower, which leads to less precise results.

The results from Stog'er Tight and Pine Cove consist only of LLHR sulphides and their interpretation is relatively simple. Four pyrite separates from Stog'er Tight have Re–Os ages ranging from 437 to 391 Ma, and contain >99% radiogenic Os. The weighted average of the model ages (Figure 3a) provides the most precise age estimate of 411.0 ± 7 Ma (2 σ; MSWD of 1.7, probability of fit of 0.17). A regression of ^{187}Os versus ^{187}Re yields a slightly younger, but less precise age of 399 ± 13 Ma, with an initial ^{187}Os content of 0.15 ± 0.14 ppt (Figure 3b). The estimate from the model ages is the preferred solution. Five separates from Pine Cove show a wide range of Re contents, from 2 to 26 ppb. The Re–Os model ages for Pine Cove separates range from 456.0 to 416.5 Ma, and they contain from 92.2 to 99.4% radiogenic ^{187}Os. The weighted average of the model ages (Figure 3c) provides the most precise age estimate of 420 ± 7 Ma (2 σ; MSWD of 1.2, probability of fit of 0.30). A regression of ^{187}Os versus ^{187}Re yields an identical, but less precise age of 420 ± 19 Ma, with an initial ^{187}Os content of -0.3 ± 3 ppt (Figure 3d).

The results obtained for pyrite separates from the Nugget Pond deposit are not so simply interpreted. Two of the four separates contain high proportions of radiogenic ^{187}Os (96 to 98%) and in this respect resemble the LLHR sulphides from the other deposits. The other two separates contain much less radiogenic ^{187}Os (2.5 and 22.6%), and model ages cannot be calculated for these results. The LLHR sulphides yield Re–Os model ages of 549.2 and 511.4 Ma, and their weighted average is 518 ± 34 Ma (MSWD of 0.73; probability of fit of 0.39). The two separates that contain common Os have similar ^{187}Re/^{188}Os, and no age estimate can be obtained from these alone. In summary, the data from Nugget Pond are problematic, and do not provide a consistent age estimate.

DISCUSSION

The results of this initial study to apply direct Re–Os dating to epigenetic gold deposits in Newfoundland are significant in two respects. The data from Stog'er Tight and Pine Cove provide new insights into the timing of gold mineralization, and suggest the possibility for wider use of this method. The close similarity in Re–Os ages obtained from pyrite separates and U–Pb ages from 'hydrothermal' zircons at Stog'er Tight suggests that the latter are indeed related to the introduction of gold. In contrast, the data from Nugget Pond are enigmatic. Not only do they not define an isochron, but the Re–Os model ages indicated by two samples are older than the inferred age of the host rocks.

Pyrites from the Stog'er Tight and Pine Cove gold deposits are LLHR sulphides (*i.e.*, ^{187}Re/^{188}Os > 5000, and >80% radiogenic ^{187}Os; Stein *et al.*, 2000). In view of these characteristics, the weighted averages of the Re–Os model ages are considered to give the best estimate of the time of gold mineralization at both deposits. These indicate an age
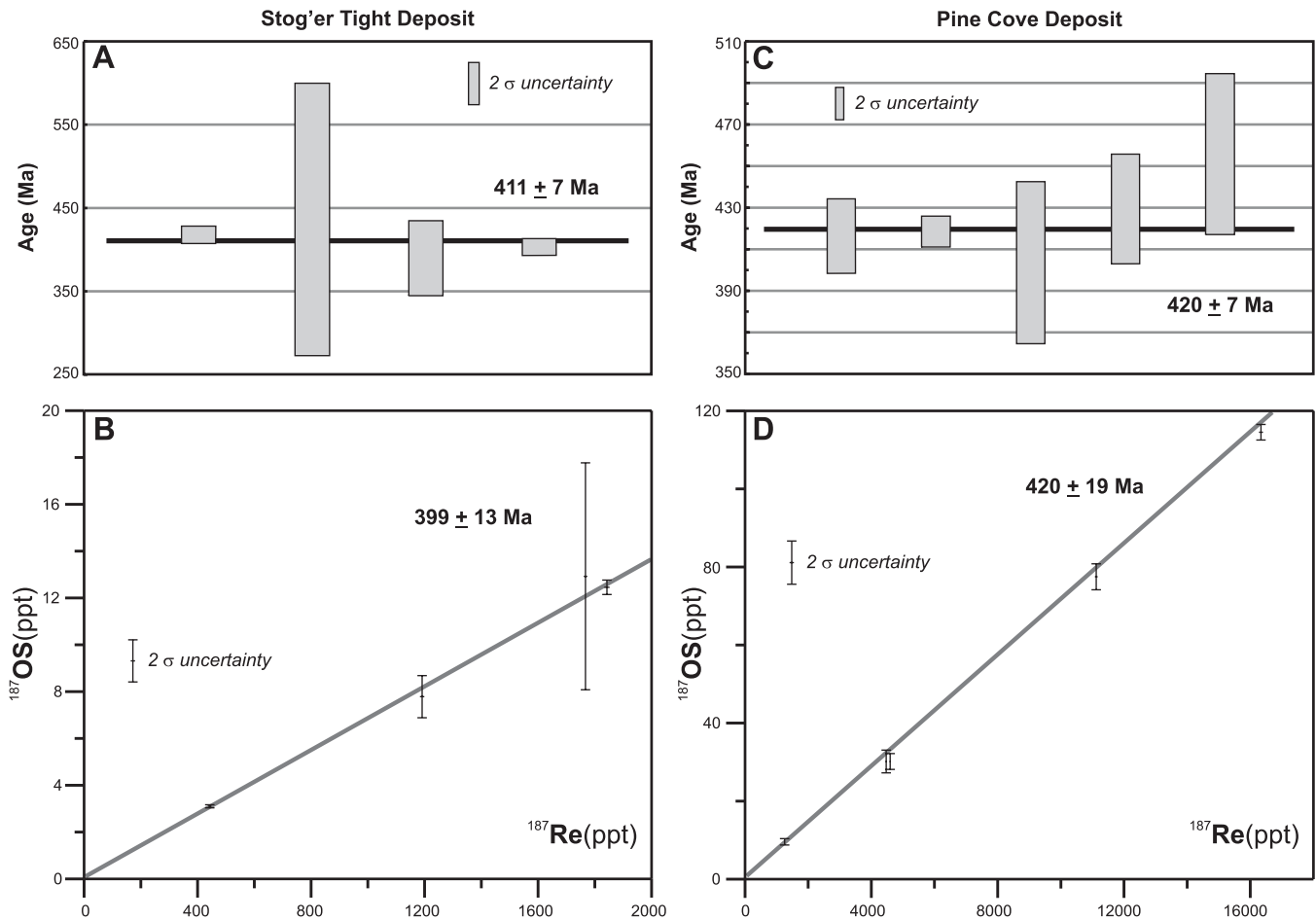
Figure 3. *(A) Re–Os model age results for the Stog'er Tight deposit; (B)* [187]*Re–*[187]*Os (parent-daughter) isochron plot for the Stog'er Tight deposit; (C) Re–Os model age results for the Pine Cove deposit; (D)* [187]*Re–*[187]*Os (parent-daughter) isochron plot for the Pine Cove deposit.*

of 411 ± 7 Ma for Stog'er Tight and 420 ± 7 Ma for Pine Cove. The Re–Os dates agree within uncertainty with the results obtained through regression of [187]Os against [187]Re (399 ± 13 and 420 ± 19 Ma, respectively). This similarity in age is consistent with the geological similarities between the two deposits. The Re–Os age for Stog'er Tight is also within uncertainty of the 420 ± 5 Ma age from 'hydrothermal' zircon (Ramezani *et al.*, 2002), suggesting that this interpretation was correct. Collectively, the data suggest that both deposits likely formed in latest Silurian or earliest Devonian times. The results also match those obtained from the Rattling Brook deposit in White Bay, dated at *ca.* 413 Ma using Ar/Ar ratio methods from pre- and post-mineralization dykes (Kerr and van Breemen, 2007). Regional structural syntheses (*e.g.*, Castonguay *et al.*, 2009; Skulski *et al.*, 2009) suggest that faults spatially associated with gold-bearing veins at these deposits and elsewhere on the Baie Verte Peninsula are D_2 structures, attributed to the Silurian Salinic Orogeny. If so, the Re–Os ages from Stog'er Tight and Pine Cove provide a general constraint on the timing of this

deformation. However, the passage of hydrothermal fluids through zones of structural weakness may significantly postdate their formation, so this can only be considered a minimum age constraint.

The data from Nugget Pond are not as easily interpreted. The Re–Os model ages from LLHR sulphides are inconsistent with the U–Pb xenotime age of 374 ± 8 Ma previously obtained from an auriferous quartz–albite–carbonate zone within the deposit (Sangster *et al.*, 2008). More importantly, the *ca.* 518 Ma model ages conflict with regional geological information because the host rocks to the gold deposit overlie the Betts Cove ophiolite, dated at *ca.* 489 Ma (Dunning and Krogh, 1985). An age of *ca.* 470 Ma was recently obtained from felsic crystal tuffs that are stratigraphically just above the host rocks (Skulski *et al.*, 2009). An age of *ca.* 518 Ma is difficult to accept, even given the relatively large uncertainty. As discussed previously, Nugget Pond differs from the other gold deposits in that mineralization was developed in rocks that already contained some sul-

phides of syngenetic or diagenetic origin. It is therefore suspected that the Re–Os results record the influence of an earlier generation of pyrite, but this cannot by itself solve the problem. Even if all of the Re in the samples (and hence all the radiogenic ^{187}Os) came from syngenetic sulphides, the Re–Os model ages cannot exceed the depositional age of the rock, unless there has been significant disturbance of Re/Os ratios. A possible explanation for this discrepancy is that these samples have lost some Re, and that their model ages are spuriously old. This possibility was investigated using preliminary numerical models, which demonstrate that the anomalous results can be reproduced with reasonable assumptions, but this does not provide proof that the explanation is correct. Addition of radiogenic ^{187}Os represents another possible explanation for spuriously old model ages, but a mechanism to accomplish this is difficult to envisage. As black shales commonly have high Os contents (*e.g.*, Selby and Creaser, 2005), microscopic inclusions of the host rock in pyrite separates may also be a contributing factor.

There are possible tests of such a model, but these require further analyses. In particular, the Re and Os contents of the Nugget Pond Horizon distal to gold mineralization need to be investigated, to see if these are sufficiently elevated. An age for the gold mineralization event may yet be obtainable if sulphide-bearing quartz–albite-carbonate veins can be isolated and analyzed; in theory, these should contain only the younger generation of sulphides. The data from Nugget Pond are puzzling, but understanding the details of this process may be important in a wider context. This is because the replacement of early syngenetic or diagenetic sulphides (or their role as a reductant for younger metalliferous fluids) is well-known to be an important process in some types of mineral deposits hosted by sedimentary rocks (*e.g.*, stratiform copper deposits). Thus, complications similar to those suggested for Nugget Pond here may bedevil other attempts at Re–Os dating.

A final point that arises from this study is the wide range of Re contents reported from individual gold deposits, in which Re contents vary by an order of magnitude. These results suggest that Re analyses of single samples from a given deposit, used to test for the feasibility of dating, may not always give representative results.

CONCLUSIONS

Despite initial frustrations, attempts to directly constrain the timing of gold mineralization in Newfoundland using Re–Os geochronology are encouraging. Pyrites from the Stog'er Tight and Pine Cove gold deposits contain sufficient Re for dating purposes, although Re contents are very low at <1 ppb Re to 26 ppb Re. The Os concentrations are extremely low, mostly less than 100 ppt (0.1 ppb), but the Os

in these pyrites is virtually all radiogenic, and they qualify as LLHR sulphides, amenable to calculation of Re–Os model ages. This approach indicates ages of 411 ± 7 and 420 ± 7 Ma for Stog'er Tight and Pine Cove, respectively. The former result is consistent with previous estimates based on U–Pb dating of zircon considered to be of hydrothermal origin. The data indicate that these two gold deposits formed in latest Silurian or earliest Devonian times, and may also constrain structural development of the region. The Re–Os data from the Nugget Pond deposit are problematic, because two LLHR samples have Re–Os model ages older than the inferred age of the host rocks. The reasons for this remain unclear, but a possible explanation is that Re originally contained in syngenetic or diagenetic sulphides was partially lost during later gold mineralization.

The major obstacle to wider application of this dating method lies in the generally low Re contents (<1 ppb) recorded from other gold deposits in Newfoundland that have so far been tested. In Paleozoic rocks, such parent isotope concentrations will not produce sufficient ^{187}Os for accurate analysis and reliable ages. Nevertheless, it is hoped that other gold deposits in Newfoundland may yet prove suitable for direct dating, and that such results will lead to a better understanding of the relationship between mesothermal (orogenic) gold mineralization and individual orogenic events recognized through regional geological studies.

ACKNOWLEDGMENTS

REFERENCES

Arne, D.C., Bierlein, F.P., Morgan, J.W. and Stein, H.J.
2001: Re-Os dating of sulfides associated with gold mineralization in central Victoria, Australia. Economic Geology, Volume 96, pages 1455-1459.

Campbell, I.H. and Naldrett, A.J.
1979: The influence of silicate : sulphide ratios on the geochemistry of magmatic sulphides. Economic Geology, Volume 74, pages 1503-1506.

Castonguay, S., Skulski, T., van Staal, C. and Currie, M.
2009: New insights on the structural geology of the Pacquet Harbour Group and Point Rousse Complex, Baie Verte Peninsula, Newfoundland. *In* Current Research. Newfoundland and Labrador Department of

Natural Resources, Geological Survey, Report 09-1, pages 147-158.

Dunning, G.R. and Krogh, T.E.
1985: Geochronology of ophiolites of the Newfoundland Appalachians. Canadian Journal of Earth Sciences, Volume 22, pages 1659-1670.

Evans, D.T.W.
2001: The Stog'er Tight gold deposit. *In* Geology and Mineral Deposits of the Northern Dunnage Zone, Newfoundland Appalachians. *Edited by* D.T.W. Evans and A. Kerr. GAC-MAC-CSPG Annual Meeting, St. John's, NL, 2001, Field Trip Guide A2, pages 71-79.

2004: Epigenetic gold cccurrences, Baie Verte Peninsula (NTS 12H/09, 16 and 12I/01), Newfoundland. Government of Newfoundland and Labrador, Department of Natural Resources, Geological Survey. Mineral Resources Report, No. 11, 157 pages.

Hibbard, J.
1983: Geology of the Baie Verte Peninsula. Newfoundland Department of Mines and Energy, Government of Newfoundland and Labrador, Memoir 2, 279 pages.

Kerr, A., Wardle, R.J., O'Brien, S.J., Evans, D.T.W. and Squires, G.C.
2005: Gold metallogeny in the Newfoundland Appalachians. GAC-MAC-CSPG-CSSS Joint Meeting, Halifax, NS, May 2005. Field Trip B9, 91 pages.

Kerr, A. and van Breemen, O.
2007: The timing of gold mineralization in White Bay, western Newfoundland: Evidence from ^{40}Ar/^{39}Ar studies of mafic dykes that predate and postdate mineralization. Atlantic Geology, Volume 43, pages 148-162.

Kerr, A., van Breemen, O. and Creaser, R.A.
2006: The timing of gold mineralization at the Rattling Brook deposit, White Bay: Constraints from Re–Os and ^{40}Ar–^{39}Ar geochronology. *In* Current Research. Newfoundland and Labrador Department of Natural Resources, Geological Survey, Report 06-1, pages 113-133.

Kirkwood, D. and Dubé, B.
1992: Structural control of sill-hosted gold mineralization: the Stog'er Tight Gold deposit, Baie Verte Peninsula, northwestern Newfoundland. *In* Current Research, Part D. Geological Survey of Canada, Report 92-1D, pages 211-221.

Lambert, D.D., Foster, J.G., Frick, L.R., Li, C. and Naldrett, A.J.
1999: Re-Os isotopic systematics of the Voisey's Bay Ni-Cu-Co magmatic ore system, Labrador, Canada. Lithos, Volume 47, pages 69-88.

Lin, S. and Corfu, F.
2002: Structural setting and geochronology of auriferous quartz veins at the High Rock Island gold deposit, northwest Superior Province, Manitoba, Canada. Economic Geology, Volume 97, pages 43-57.

Ludwig, K.R.
2003: User's manual for Isoplot/Ex rev. 3.00: A geochronological toolkit for Microsoft Excel. Berkely Geochronology Centre, Special Publication 4, 70 pages.

Lynch, E.P., Selby, D., Feely, M. and Wilton, D.H.C.
2009: New constraints on the timing of molybdenite mineralization in the Devonian Ackley Granite suite, southeastern Newfoundland: Preliminary results from Re–Os geochronology. *In* Current Research. Newfoundland Department of Natural Resources, Geological Survey, Report 09-1, pages 225-235.

McNicoll, V., Squires, G.C., Wardle, R.J., Dunning, G.R. and O'Brien, B.H.
2006: U–Pb geochronological evidence for Devonian deformation and gold mineralization in the eastern Dunnage Zone, Newfoundland. *In* Current Research. Newfoundland and Labrador Department of Natural Resources, Geological Survey, Report 06-1, pages 43-60.

Morelli, R.M., Creaser, R.A., Selby, D., Kontak, D. J. and Horne, R.J.
2005: Rhenium-osmium geochronology of arsenopyrite in Meguma Group gold deposits, Meguma Terrane, Nova Scotia, Canada: Evidence for multiple gold-mineralizing events. Economic Geology, Volume 100, pages 1229-1242.

Pettke, T., Diamond, L.W. and Villa, I.M.
1999: Mesothermal gold veins and metamorphic devolatilization in the northwestern Alps: The temporal link. Geology, Volume 27, pages 641-644.

Ramezani, J.
1992: The geology, geochemistry and U-Pb geochronology of the Stog'er Tight Gold Prospect, Baie Verte peninsula, Newfoundland. Unpublished M. Sc. thesis, Memorial University of Newfoundland, 256 pages.

Ramezani, J., Dunning, G.R. and Wilson, M.R.
　2002: Geologic setting, geochemistry of alteration, and U-Pb age of hydrothermal zircon from the Silurian Stog 'er Tight gold prospect, Newfoundland Appalachians, Canada. Exploration and Mining Geology, Volume 9, pages 171-188.

Ritcey, D.H., Wilson, M.R., and Dunning, G.R.
　1995: Gold mineralization in the Paleozoic Appalachian Orogen: Constraints from geologic, U-Pb and stable isotope studies of the Hammerdown prospect, Newfoundland. Economic Geology, Volume 90, pages 1955-1965.

Sangster, A.L., Douma, S.L. and Lavigne, J.
　2008: Base metal and gold deposits of the Betts Cove Complex, Baie Verte Peninsula, Newfoundland. Geological Association of Canada, Mineral Deposits Division, Special Publication 5, pages 703-723.

Selby, D. and Creaser, R.A.
　2005: Direct radiometric dating of the Devonian-Mississippian time-scale boundary using the Re-Os black shale geochronometer. Geology, Volume 44, pages 545-548.

Selby, D., Kelley, K.D., Hitzman, M.W. and Zeig, J.
　2009: Re-Os sulfide (bornite, chalcopyrite and pyrite) systematics of the carbonate-hosted copper deposits at Ruby Creek, southern Brooks Range, Alaska. Economic Geology, Volume 104, pages 437-444.

Skulski, T., Castonguay, S., van Staal, C.R., Rogers, N., McNicoll, V., Kerr, A. and Escayola, M.
　2009: Baie Verte Peninsula: An evolving geological story. Geological Association of Canada (Newfoundland and Labrador Section), 2009 Fall Field Trip Guide, 58 pages.

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

Stein, H.J., Morgan, J.W. and Schersten, A.
　2000: Re-Os dating of low-level highly radiogenic (LLHR) sulfides; the Harnas gold deposit, southwest Sweden, records continental-scale tectonic events. Economic Geology, Volume 95, pages 1657-1671.

Swinden, H.S., McBride, D.M. and Dubé, B.
　1990: Preliminary geological and mineralogical notes on the Nugget Pond gold deposit, Baie Verte Peninsula, Newfoundland. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 90-1, pages 201-215.

Swinden, H.S., Evans, D.T.W. and Kean, B.F.
　2001: Regional geology and metallogeny of central Newfoundland. *In* Geology and Mineral deposits of the northern Dunnage Zone, Newfoundland Appalachians. *Edited by* D.T.W. Evans and A. Kerr. GAC-MAC-CSPG Annual Meeting, St. John's, NL, 2001, Field Trip Guide A2, pages 1-17.

Thorne, K.G., Lentz, D.R., Hall, D.C. and Yang, X.
　2002: Petrology, geochemistry and geochronology of the granitic pegmatite and aplite dykes associated with the Clarence Stream gold deposit, southwestern New Brunswick. Geological Survey of Canada, Current Research 2002-E12, 13 pages.

Tuach, J., Dean, P.L., Swinden, H.S., O'Driscoll, C., Kean, B.F. and Evans, D.T.W.
　1988: Gold mineralization in Newfoundland: a 1988 review. *In* Current Research. Newfoundland Department of Mines, Mineral Development Division, Report 88-1, pages 279-306.