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## TACONIAN OROGENESIS, SEDIMENTATION AND MAGMATISM IN THE SOUTHERN QUEBEC–NORTHERN VERMONT APPALACHIANS: STRATIGRAPHIC AND DETRITAL MINERAL RECORD OF IAPETAN SUTURING

STÉPHANE DE SOUZA*,†, ALAIN TREMBLAY*, and GILLES RUFFET**

**ABSTRACT. Cambrian-Ordovician units of the southern Quebec Appalachians oceanic domain include obducted ophiolites and an overlying syncollisional sedimentary basin represented by the Saint-Daniel Mélange and flysch units of the Magog Group. These terrains were thrust onto the Laurentian continental margin during the Taconian orogeny and are unconformably overlain by Silurian-Devonian successor basins. This contribution presents and discusses new stratigraphic data acquired in the oceanic domain, as well as U-Pb and $^{40}Ar/^{39}Ar$ geochronological data on detrital zircons and muscovites sampled at various stratigraphic levels, from the base of the sedimentary units of the oceanic domain and the Silurian-Devonian units of the Gaspé Belt. This work, combined with the compilation of existing data for southern Quebec and western New England allows a better definition of the tectono-stratigraphic evolution of the area, and are used to propose correlations with different rock units of the northern New England Appalachians, which represents a collage of Laurentian margin and oceanic units. It is shown that Cambrian-Ordovician rocks of southern Quebec and northern Vermont have undergone a similar tectonic evolution. The ophiolites were obducted onto the Laurentian margin as a more or less coherent slab of oceanic lithosphere. Both the ophiolites and continental margin rocks were uplifted, eroded and unconformably overlain by Middle to Late Ordovician units of the Saint-Daniel Mélange and Magog Group in a forearc setting. The presence of mafic and felsic volcanic flows that are interstratified within the Saint-Daniel Mélange can be correlated with an episode of delamination and slab breakoff during the final stages of obduction and exhumation of the orogenic wedge. The Magog Group was deposited during the emplacement of the Taconian nappes, as the outboard volcanic arc was still active but progressively shutting down. The provenances suggested by the age of the dated detrital minerals can be entirely reconciled with the peri-Laurentian context of the studied rock units and testify of the tectonic evolution and sedimentary recycling of the Taconian orogen, from ophiolite obduction onto the Laurentian margin, to the collapse of the orogenic belt and the formation of successor basins.**

Key words: Taconian orogeny, Appalachians, forearc basin, ophiolite, obduction, Humber Zone, Dunnage Zone, Gaspé Belt, detrital zircon, detrital muscovite, geochronology, U-Pb, $^{40}Ar/^{39}Ar$

### INTRODUCTION

The Cambrian-Ordovician Taconian orogeny is a first order lithotectonic feature of the Northern Appalachians that involves the emplacement of large ophiolitic

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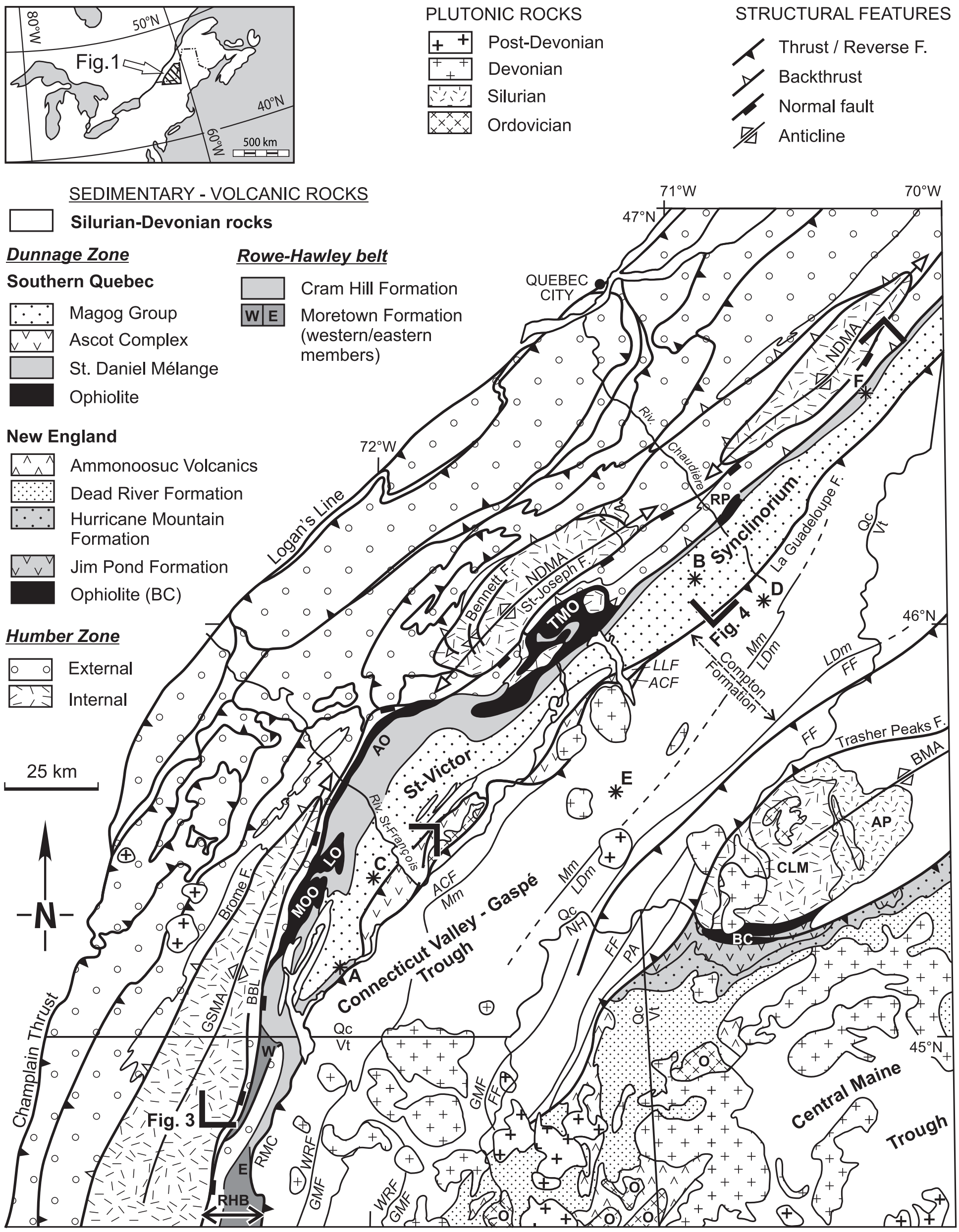


Fig. 1. Geological map of the southern Quebec and western New England Appalachians (after Slivitzky and St-Julien, 1987; Moench and others, 1995; Tremblay and Castonguay, 2002; Castonguay and others, 2002; Moench and Aleinikoff, 2002; Hibbard and others, 2006; McWilliams and others, 2010). The Rowe-Hawley belt of northern Vermont includes the Stowe, Moretown and Cram Hill formations. Stratigraphic units of the Connecticut Valley–Gaspé trough are identified by labels in italic. The Gaspé Belt in Quebec: *ACF*—Ayers Cliff Formation; *FF*—Frontenac Formation; *LDm*—Lac Drolet member; *LL*—Lac Lambton Formation; *Mm*—Milan member. The Connecticut Valley sequence of Vermont: *GMF*—Gile Mountain Formation; *PA*—Piermont allochthon; *WRF*—Waits River Formation. AO—Asbestos ophiolite; BBL—Baie Verte-Brompton line; BC—Boil Mountain Complex; BMA—Boundary Mountains Anticlinorium; GSMA—Green and Sutton Mountains anticlinorium; LO—Lac-Brompton ophiolite; MOO—Mont-Orford ophiolite; NDMA—Notre-Dame Mountains Anticlinorium; O—Oliverian Plutonic Suite; RHB—Rowe-Hawley belt; RMC—Richardson-Memorial contact; RP—Rivière-des-Plante ultramafic Complex; Thetford-

nappes onto Laurentia and the accretion of volcanic arcs and continental blocks as a result of the closure of the Iapetus Ocean and ongoing convergence between Laurentia and Gondwana (St-Julien and Hubert, 1975; Williams, 1979; Stanley and Ratcliffe, 1985; Tremblay, 1992a; Pinet and Tremblay, 1995; Karabinos and others, 1998; van Staal and others, 1998; van Staal, 2007). Evidence for Taconian orogenesis and suturing is particularly well-preserved in the southern Quebec and Vermont Appalachians, which can be divided into three main lithotectonic assemblages: the Early Paleozoic Humber and Dunnage zones, and the overlying Silurian-Devonian successions of the Connecticut Valley-Gaspé trough (fig. 1; Williams, 1979; Bourque and others, 2000; Lavoie and Asselin, 2004; Tremblay and Pinet, 2005; Rankin and others, 2007). The Humber and Dunnage zones were amalgamated during the Taconian orogeny and represent, respectively, vestiges of the Laurentian continental margin and adjacent oceanic basin (Williams, 1979). Although many plate tectonic models have been proposed for the evolution of the southern Quebec-Vermont Appalachians, these interpretations are hindered by scarce geochronological constraints and by poor understanding of various lithostratigraphic components of the Dunnage zone, and their significance in paleotectonic reconstructions (Doolan and others, 1982; Tremblay, 1992a; Pinet and Tremblay, 1995).

In this contribution we present detailed field observations and detrital zircon U-Pb and muscovite $^{40}Ar/^{39}Ar$ geochronological data for volcanic and sedimentary rocks of the Dunnage zone and the Connecticut Valley-Gaspé trough of southern Quebec. It will be shown that these syn- to post-orogenic units form an almost continuous lithostratigraphic record of Ordovician to Devonian basin formation and ongoing tectonics. The stratigraphy, age, and provenance of the studied rock units can be reconciled with the regional stratigraphic framework of the southern Quebec and northern Vermont Appalachians in order to propose a comprehensive tectonic model for this part of the Taconian orogen, from the emplacement of ophiolitic nappes onto Laurentia and formation of an onlapping forearc basin during the Ordovician, to formation of successor basins in the Silurian to Early Devonian.

## REGIONAL SETTING

### *The Southern Quebec–Northern New England Appalachians*

In southern Quebec and New England, the Humber zone consists of a fold-and-thrust belt that is represented by Neoproterozoic to Early Ordovician siliciclastic and minor basaltic rift and passive margin rocks, which are subdivided into a subgreenschist grade external zone and an upper greenschist to amphibolite facies internal zone (fig. 1). The internal Humber zone is limited to the southeast by a series of major normal faults known as the Baie Verte-Brompton line–Saint-Joseph fault in southern Quebec (Pinet and others, 1996; Tremblay and Castonguay, 2002; Castonguay and Tremblay, 2003), which extends into Vermont as the Burgess Branch fault zone (Kim and others, 1999; Castonguay and others, 2012). Dunnage zone rocks are exposed to the southeast of the Baie Verte–Brompton line as part of the Saint-Victor synclinorium in southern Quebec and of the Rowe-Hawley belt in northern Vermont (fig. 1; Doolan and others, 1982; Tremblay, 1992a). The Connecticut Valley–Gaspé trough is located to the southeast of the La Guadeloupe fault and is underlain by Silurian-Devonian rocks that form part of the Gaspé Belt in southern Quebec (Tremblay and Pinet, 2005) and that can be mapped continuously southward into western New England, where it is

Fig. 1 (continued). Mines ophiolite; UT—Underhill Thrust. Asterisks indicate the location of sampling sites for the U-Pb and $^{40}Ar/^{39}Ar$ data presented in this study: A—samples 07BUNKER and 10BUNKER01; B—09SV01; C—09SV02; D—09MILAN01; E—09MILAN02; F—08M44.

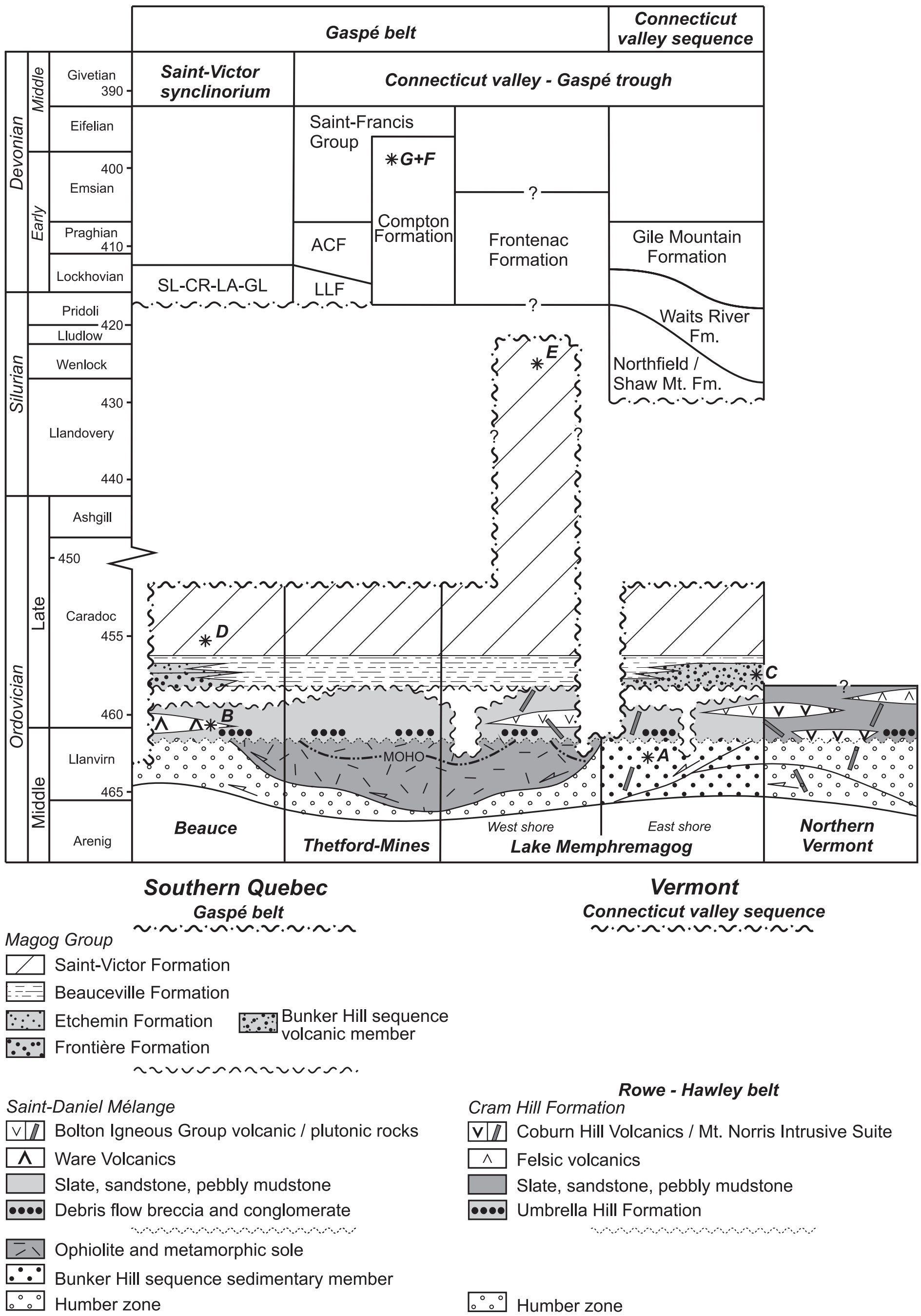


Fig. 2. Schematic correlation chart for the Humber and Dunnage zones of the Beauce, Thetford-Mines, and Lake Memphremagog areas, and the various units of the Gaspé Belt of southern Quebec. Inferred correlations with the Rowe–Hawley belt and Connecticut Valley sequence of Vermont are also illustrated. See text for discussion. ACF—Ayers Cliff Formation; CR—Cranbourne Formation; GL—Glenbrooke Group; LA—Lac Aylmer Formation; LLF—Lac Lambton Formation; SL—Saint-Luc Formation. The samples presented in the text are symbolized by asterisks: *A*—07BUNKER; *B*—08M44; *C*—10BUNKER01; *D*—09SV01; *E*—09SV02; *F*—09MILAN02; *G*—09MILAN01. The wavy lines highlight the presence of unconformities.

informally referred to as the Connecticut Valley sequence (fig. 1; Rankin and others, 2007; McWilliams and others, 2010). A revised stratigraphic correlation chart for the study area is presented in figure 2 and illustrates new and previously proposed interpretations, as well as the position of the stratigraphic units and unconformities presented and discussed herein.

*The southern Quebec Dunnage zone.*—The Dunnage zone of southern Quebec includes 1) a series of well-preserved to dismembered ophiolite complexes; 2) the Saint-Daniel Mélange; 3) the Magog Group; and 4) the Ascot Complex (fig. 1).

The ophiolites occur on the northwestern limb of the Saint-Victor synclinorium and represent correlative remnants of obducted suprasubduction zone ophiolites made up of oceanic crust and mantle, and of sub-ophiolitic metamorphic sole rocks (Schroetter and others, 2003; De Souza and others, 2008, 2012; Tremblay, and others, 2011). U-Pb zircon ages for ophiolitic plagiogranites vary from 504 $\pm$ 3 Ma in the Mont-Orford ophiolite (David and Marquis, 1994), to 478 $+3/-2$ and 480 $\pm$ 2 Ma in the Thetford-Mines ophiolite (Whitehead and others, 2000).

The Saint-Daniel Mélange is exposed on both limbs of the Saint-Victor synclinorium and was previously interpreted as an accretionary complex dominantly composed of an argillaceous-to-conglomeratic matrix with deca- to kilometer-scale olistoliths and lithotectonic slivers of ophiolitic, sedimentary and volcanic rock units, such as the Bolton Igneous Group and Bunker Hill sequence in the Lake Memphremagog area, and the Ware Volcanics in the Beauce area (figs. 1, 3, and 4; Doolan and others, 1982; Cousineau and St-Julien, 1992; Tremblay, 1992a). Recent work has rather shown that the Saint-Daniel Mélange represents the lower part of a syncollisional sedimentary basin that unconformably overlies various stratigraphic levels of the ophiolites including crustal, mantle and sub-ophiolitic metamorphic rocks (figs. 2 and 3; Schroetter and others, 2006; De Souza and others, 2008; De Souza and Tremblay, 2010a). Pillowed basaltic-to-andesitic rocks, diabase and gabbro of the Bolton Igneous Group form conformable horizons of volcanic rocks and related dikes and/or sills interlayered within and crosscutting the Saint-Daniel Mélange (Doolan and others, 1982; Rickard, 1991; Mélançon and others, 1997; De Souza, ms, 2012), whereas the Ware Volcanics are made up of dacitic to rhyolitic volcanic rocks occurring as lens-shaped bodies within siltstone and slate of the Saint-Daniel Mélange in the Beauce area (fig. 4; Cousineau and St-Julien, 1992; De Souza, ms, 2012). The Bunker Hill sequence is a volcano-sedimentary rock assemblage that is divided into two informal members: a volcanic member consisting of pyroclastic and volcaniclastic rocks and a sandstone-dominated sedimentary member petrographically similar to the Caldwell Group of the Humber zone (Blais, ms, 1991; Tremblay, 1990).

The Magog Group comprises a *ca.* 10 km-thick Middle to Late Ordovician flysch succession that unconformably overlies the Saint-Daniel Mélange (figs. 3 and 4; Cousineau and St-Julien, 1994; Schroetter and others, 2006).

The Ascot Complex represents the remnants of a peri-Laurentian volcanic arc (fig. 3; Tremblay and others, 1989; Tremblay, 1992a). It is composed of felsic and mafic volcanic rocks and a syn-volcanic pluton that are overlain by, and in fault contact with pebbly phyllites that correlate with those of the Saint-Daniel Mélange (Tremblay and others, 1989; Gauthier and others, 1989; Tremblay and St-Julien, 1990). Felsic volcanic rocks and granite belonging to the Ascot Complex have yielded U-Pb zircon ages of

Fig. 2 (continued). The stratigraphic nomenclature for the Gaspé and Rowe-Hawley belts are from Lavoie and Asselin (2004) and Doolan and others (1982), whereas the one of the Connecticut Valley sequence is shown as compiled in McWilliams and others (2010). The Ordovician-Silurian and Devonian time scales are from Sadler and others (2009) and Gradstein and others (2004), respectively. Note change in time scale at 450 Ma.

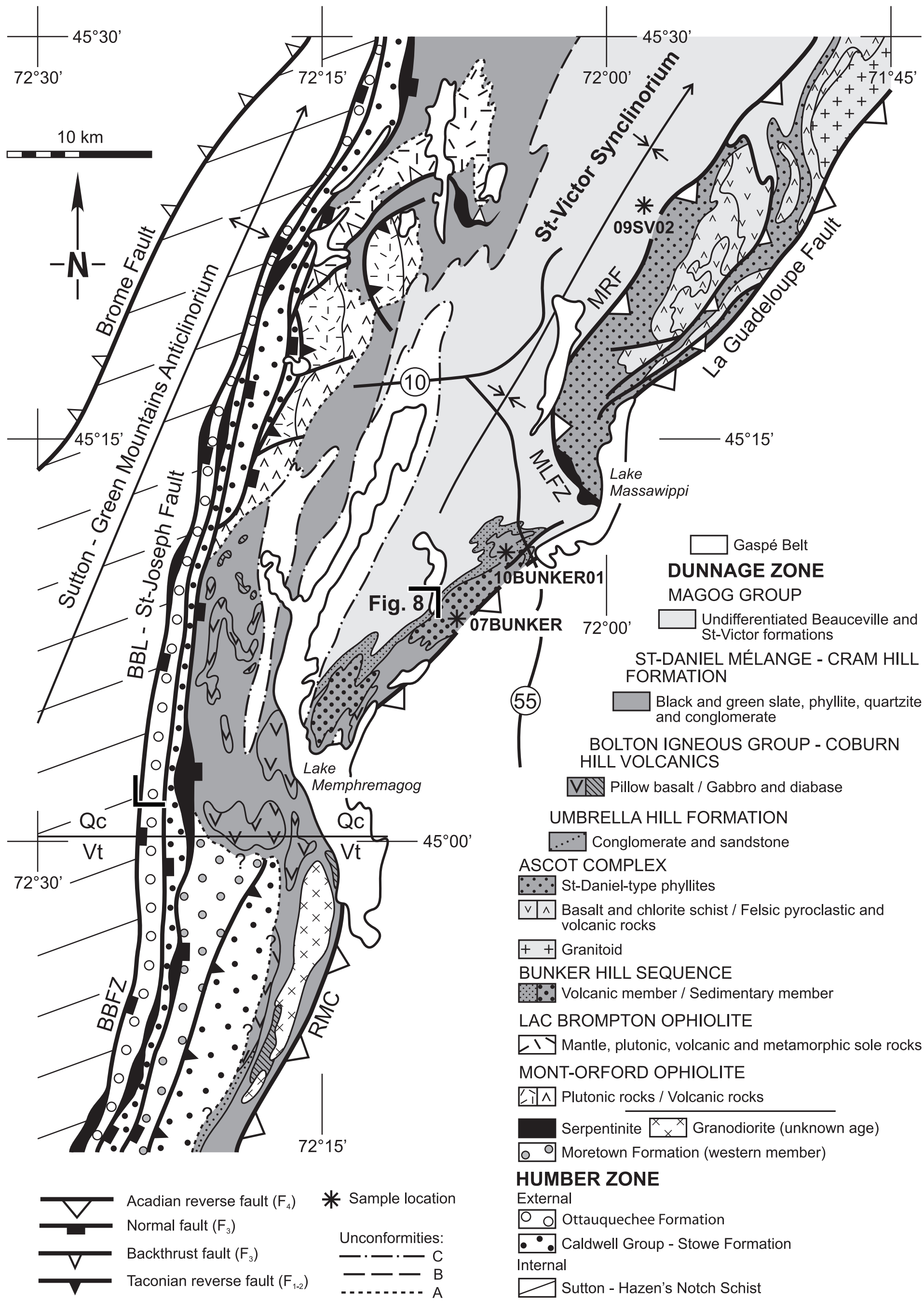


Fig. 3. Geological map of the Lake Memphremagog area in southern Quebec and northen Vermont (after Lamothe, 1979, 1981a, 1981b; Gale, ms, 1980; De Romer, 1980; Doolan and others, 1982; Slivitzky and St-Julien, 1987; Rickard, 1991; Tremblay, 1990, 1992b; Huot, ms, 1997; Kim and others, 1999; De Souza and others, 2008). BBFZ—Burgess Branch fault zone; BBL—Baie Verte-Brompton line; MLFZ—Massawippi Lake fault zone; MRF—Magog River fault; other symbols as in figure 1. See figure1 for location.

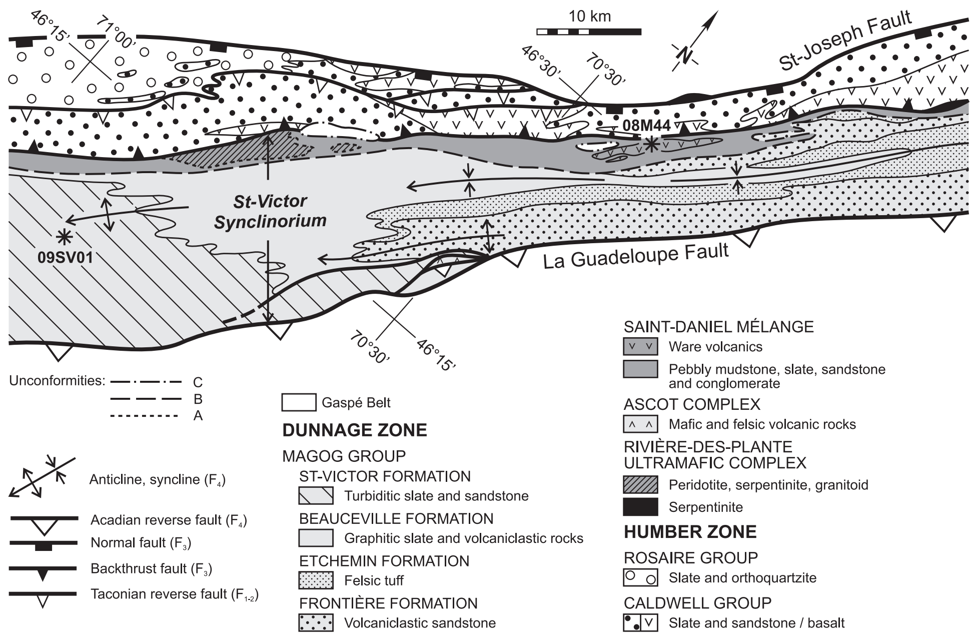


Fig. 4. Geological map of the Beauce area (after Cousineau, 1986, 1990; St-Julien, 1987; De Souza and Tremblay, 2010a). Asterisks indicate sample locations. See figure 1 for location.

460 ± 3 Ma and 441 +7/−12 Ma (David and Marquis, 1994), and an $^{40}Ar$-$^{39}Ar$ muscovite age of 462 ± 2 Ma (Tremblay and others, 2000).

*The Vermont Rowe-Hawley belt.*—Dunnage and Humber zone rocks of southern Quebec can be mapped continuously into the Vermont Rowe-Hawley belt (figs. 1 and 2; Doolan and others, 1982). The main stratigraphic correlations across the Quebec–Vermont international border are summarized and illustrated in the geologic map of figure 3. Well-preserved ophiolites are not present in northern Vermont, but amphibolites, serpentinites, felsic gneisses and granitoid rocks discontinuously exposed from central Vermont to Connecticut are believed to represent dismembered Early Ordovician forearc-arc-backarc terranes (for example, the Shelburne Falls arc; Stanley and Ratcliffe, 1985; Kim and Jacobi, 1996, 2002; Karabinos and others, 1998). The Saint-Daniel Mélange is mapped into Vermont as the Cram Hill Formation (Doolan and others, 1982 and references therein). The contact between the Cram Hill Formation and the underlying Stowe Formation, which correlates with the Caldwell Group of the southern Quebec Humber zone, is marked by the Umbrella Hill Formation conglomerate and has been interpreted either as an unconformity (Doolan and others, 1982; De Souza and Tremblay, 2010b) or a fault (Stanley and Ratcliffe, 1985; Kim and others, 1999). Quartz arenite, feldspathic sandstone and phyllite of the Moretown Formation of Vermont do not have any known counterpart in southern Quebec and have been divided into western and eastern informal members (Kim and others, 1999), that either represent part of the Humber or Dunnage zone, or both (Rowley and Kidd, 1981; Doolan and others, 1982; Stanley and Ratcliffe, 1985; Kim and others, 1999; Kim, 2006; De Souza and Tremblay, 2010b). The Bolton Igneous Group of southern Québec has been correlated with the Coburn Hill Volcanics and the Mount Norris Intrusive Suite (Kim and others, 2003). The latter consists of diabase dikes that cut across previously-foliated rocks of the Moretown and Stowe formations, and have been interpreted as the result of syn-tectonic Taconian magmatism (Kim and others, 2003).

*The Gaspé Belt.*—In southern Quebec, the Gaspé Belt is made up of two stratigraphic assemblages of Silurian to Early Devonian age (Lavoie and Asselin, 2004). The first assemblage is distributed in a series of synformal outliers that unconformably overlie Dunnage and/or Humber zone rocks to the northwest of the La Guadeloupe fault (fig. 1), whereas the second assemblage underlies the Connecticut Valley–Gaspé trough and is represented by siliciclastic rocks of the the Saint-Francis Group and volcano-sedimentary rocks of the Frontenac Formation (fig. 1). Various tectonic settings have been proposed for the formation of the Connecticut Valley-Gaspé trough [see Tremblay and Pinet (2005) and Rankin and others (2007) for a review] but there is a growing general consensus relating this sedimentary basin to delamination-related extension (van Staal and de Roo, 1995; Robinson and others, 1998; Tremblay and Pinet, 2005; Rankin and others, 2007; McWilliams and others, 2010).

### *Tectonic Synthesis*

The southern Quebec Dunnage and Humber zones and the Rowe-Hawley belt have undergone a threefold tectonic evolution, with evidence of deformation and metamorphism during the Ordovician, the Silurian to Early Devonian and the Middle Devonian (Tremblay and Castonguay, 2002; Castonguay and others, 2012). The oldest structural fabric is a $S_{1\text{-}2}$ composite foliation that is attributed to ophiolite emplacement and northwest-directed thrusting of the Humber zone allochthonous nappes during the Taconian orogeny, and has been isotopically dated at 471 to 450 Ma (Tremblay and Pinet, 1994; Castonguay and others, 2001, 2007, 2012; Sasseville and others, 2008; Tremblay and others, 2011; De Souza and others, 2012). Hinterland-directed (that is southeast) deformation related to post-Taconian backthrusting resulted in the formation of a $S_3$ foliation and northwest-dipping thrust faults (for example, the Brome–Bennett fault; fig. 1), and culminated with normal faulting along the Saint-Joseph–Baie Verte-Brompton line and Burgess Branch fault zones in southern Quebec and northern Vermont, respectively (Tremblay and Pinet, 2005; Castonguay and others, 2012). This latter episode of regional deformation has been attributed a Silurian-Early Devonian age (*ca.* 435-405 Ma) based on $^{40}Ar/^{39}Ar$ dating of Humber zone rocks (Castonguay and others, 2001, 2007, 2012; Sasseville and others, 2008). Finally, Middle Devonian regional metamorphism and related deformation, between *ca.* 390 to 360 Ma, is present and attributed to the Acadian orogeny (Laird and others, 1984; Tremblay and others, 2000; Castonguay and others, 2001, 2007). It is related to a regional penetrative foliation that forms the oldest structural fabric in rocks of the Gaspé Belt and correlative units of New England (Osberg and others, 1989; Cousineau and Tremblay, 1993; Tremblay and others, 2000; Castonguay and others, 2012).

## GEOCHRONOLOGIC AND STRATIGRAPHIC DATA

Field work for this study was mostly conducted in the Beauce and Lake Memphremagog areas, which represent the northeastern and southwestern extremities of the Saint-Victor synclinorium and are underlain by Humber and Dunnage zone rocks. The main structural and stratigraphic features that have been recognized in both areas are illustrated in figures 2, 3 and 4.

Rock units that were studied and sampled for primary and detrital are The Bolton Igneous Group, the Bunker Hill sequence and the Ware Volcanics of the Saint-Daniel Mélange, the turbidites of the Magog Group and Silurian-Devonian siliciclastic rocks of the Compton Formation. These rock units have recorded ongoing tectonic events from the obduction of ophiolites during the Ordovician, to the formation of post-Taconian successor basins during the Silurian-Devonian and are thus instrumental in the interpretation of the paleotectonic history of the Northern Appalachians. The stratigraphic setting of these units and of the various sampling sites is presented in the following sections with the corresponding isotopic age results. The Bolton Igneous Group intrusive facies and the Ware Volcanics have not yielded a sufficient amount of zircon grains for the determination of crystallization ages and most of the separated zircons revealed to be of inherited origin in the Ware Volcanics (see Appendix 1).

### *Analytical Procedures*

Zircon mineral concentrates were prepared from samples of crushed rock by using standard density and magnetic separation techniques. Zircon crystals were extracted from concentrates by handpicking under a binocular microscope, mounted in epoxy and polished for analysis by LA-MC-ICP-MS (laser ablation–magnetic sector–inductively coupled plasma–mass spectrometry). The analyses were conducted at the University of Alberta, Edmonton, Alberta, by using the analytical protocol of Simonetti and others (2005). The analyses that are less than 30 percent discordant are shown in Appendix 1 and illustrated as probability density distribution diagrams in figure 5. Unless mentioned, the $^{206}Pb/^{238}U$ ages are used for zircons younger than *ca.* 1000 Ma, whereas the $^{207}Pb/^{206}Pb$ ages are used for zircons older than *ca.* 1000 Ma. However, although less precise for zircons younger than *ca.* 1000 Ma, $^{207}Pb/^{206}Pb$ ages are generally more accurate and less sensitive to lead loss and instrumental fractionation relative to the $^{206}Pb/^{238}U$ ratio (Gehrels, 2012), and are preferably used for the calculation of weighted mean ages when they form age clusters. Age clusters used for age determinations and the calculation of weighted mean ages were defined as a series of at least six $^{207}Pb/^{206}Pb$ or $^{206}Pb/^{238}U$ ages that overlap with 2σ error bars and have a 2σ uncertainty of less that 10 percent. Error bars of 1σ are used in the probability density distribution diagrams, whereas all ages are reported in text at the 2σ level. Cathodoluminescence imaging was conducted at the Microscopy and Microanalysis Facility, University of New Brunswick, Fredericton, New Brunswick, the results of which are summarized in figure 6.

For the $^{40}Ar/^{39}Ar$ analyses, muscovite grains were handpicked from the same samples that were processed for the zircon concentrates. Single muscovite grains were then analyzed by laser step-heating at the CNRS-Université de Rennes 1, Rennes, France, following an analytical procedure detailed by Ruffet and others (1991, 1995) and Castonguay and others (2001, 2007). Plateau ages were calculated using a minimum of three consecutive steps representing at least 70 percent of the $^{39}Ar$ released and have apparent ages that agree within 2σ error bars with the integrated age of the plateau segment (Castonguay and others, 2001). All of the muscovite plateau ages are reported in text and in figure 7 using 1σ error bars.

### *The Bunker Hill Sequence*

The Bunker Hill sequence is a volcano-sedimentary rock assemblage that is divided into two informal members: a volcanic member consisting of pyroclastic and volcaniclastic rocks and a sandstone-dominated sedimentary member (figs. 3 and 8; de Romer, 1980; Tremblay, 1990; Blais, ms, 1991). The sedimentary member consists of a monotonous succession of interstratified green to gray and poorly-sorted feldspathic graywacke with discontinuous lenses of quartz-pebble conglomerate, siltstone and mudslate. The major constituents of the graywacke are angular to sub-rounded grains of quartz, plagioclase, K-feldspar, quartzite and granitoid. Younging directions observed in the Bunker Hill sedimentary member are opposite to those found in the overlying Magog Group, which suggests the occurrence of a discontinuity between both units (Tremblay, 1990). Moreover, clasts of foliated green to gray feldspathic graywacke petrographically similar to the one of the sedimentary member (figs. 9A and 9B) are locally found within conglomerate of the Saint-Daniel Mélange, suggesting

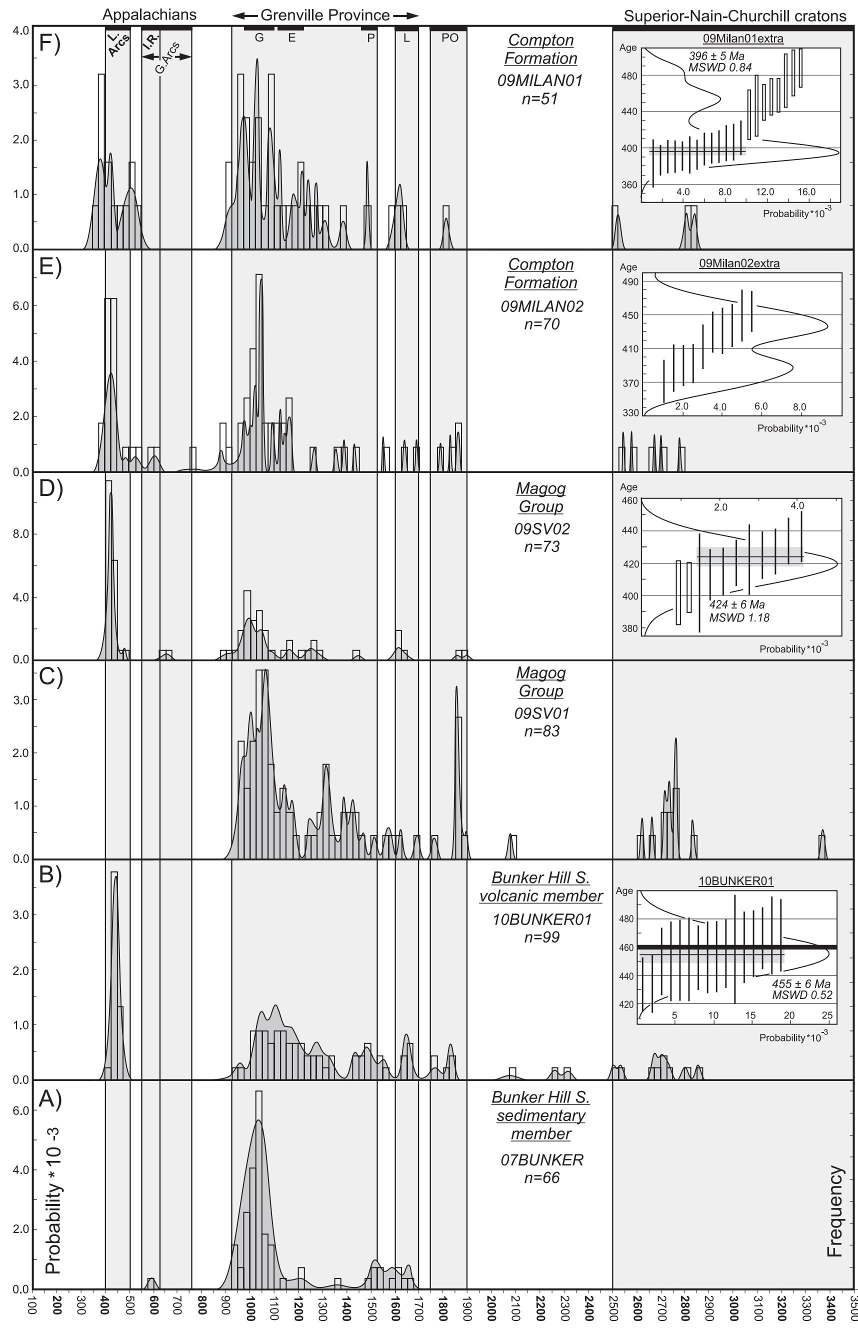


Fig. 5. Probability density distribution–frequency diagrams of detrital zircon ages for samples of (A) the Bunker Hill sequence sedimentary member—07BUNKER and (B) volcanic member—10BUNKER01; the Magog Group (C) 09SV01, (D) 09SV02; and the Compton Formation (E) 09MILAN02, (F) 09MILAN01. The age–probability density distribution plots shown in the insets of (B), (D) and (F) are for the youngest age clusters from which were calculated weighted mean ages; ages illustrated by empty boxes were excluded from mean calculations. Insets show ages that are *ca.* 90 percent to 105 percent concordant. Note that in the inset of (F), the ages do not form an age cluster (see text for explanation). All the probability density

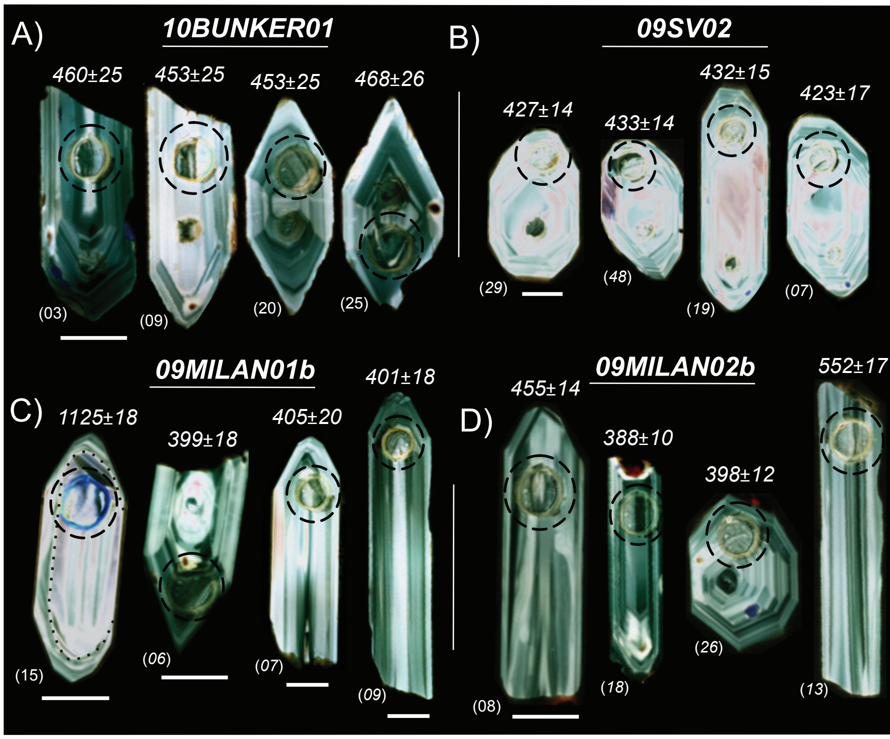


Fig. 6. Cathodoluminescence images of dated zircons from (A) the Bunker Hill sequence volcanic member—10BUNKER01; (B) Saint-Victor Formation—09SV02; (C) extra grain sets Compton Formation—09MILAN01b and (D)—09MILAN02b. Dashed lines highlight laser ablation pits and dotted lines delimit inherited zircon cores. The ages of the dated grains are indicated in italic, whereas the numbers in parentheses correspond to the grain numbers of Appendix 1. Scale bars are all 50 μm.

that the Bunker Hill sedimentary member was deformed and overturned prior to the deposition of the Saint-Daniel Mélange.

The volcanic member occurs to the northwest of the sedimentary member and is best exposed in a quarry near Massawippi Lake (fig. 10). It is made up of felsic tuff and chert interlayered with volcanic conglomerate, volcaniclastic sandstone and black phyllite (fig. 9C). A unique characteristic of the volcanic conglomerate and volcaniclastic sandstone is that they both contain bright, green-colored millimetric to centimetric clasts of fuchsite- and chromite-bearing clasts. The volcanic conglomerate is however mostly made up of tuffaceous fragments, with minor amounts of granitic, volcaniclastic

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Fig. 5 (continued). distribution plots were generated using AgeDisplay (Sircombe, 2004), whereas weighted mean ages were calculated with Isoplot (Ludwig, 2003). Light gray shaded areas in the background highlight main episodes of continental crust formation and magmatism in the southeastern Superior Province (Wardle and others, 2002; Percival, 2007), the Grenville Province and Paleoproterozoic orogens of the southeastern Canadian Shield (Wardle and others, 2002; Gower and Krogh, 2002; Tollo and others, 2004), Iapetan rift magmatism (Cawood and others, 2001), peri-Gondwanan Avalonian-Ganderian arcs (O'Brien and others, 1996) and peri-Laurentian arcs and ophiolites (Tucker and Robinson, 1990; David and Marquis, 1994; Kusky and others, 1997; Karabinos and others, 1998; Whitehead and others, 2000; Moench and Aleinikoff, 2002; Gerbi and others, 2006). E—Elzevirian Orogeny; G—Grenvillian Orogeny; G.Arcs—peri-Gondwanan arcs; IR Iapetan riftmagmatism; L.Arcs—peri-Laurentian arcs; P—Pinwarian Orogeny; L—Labradorian Orogeny; PO—Paleoproterozoic orogens: New Quebec, Torngat and Makkovik orogens. n—represents the number of analyses presented in the corresponding diagram.

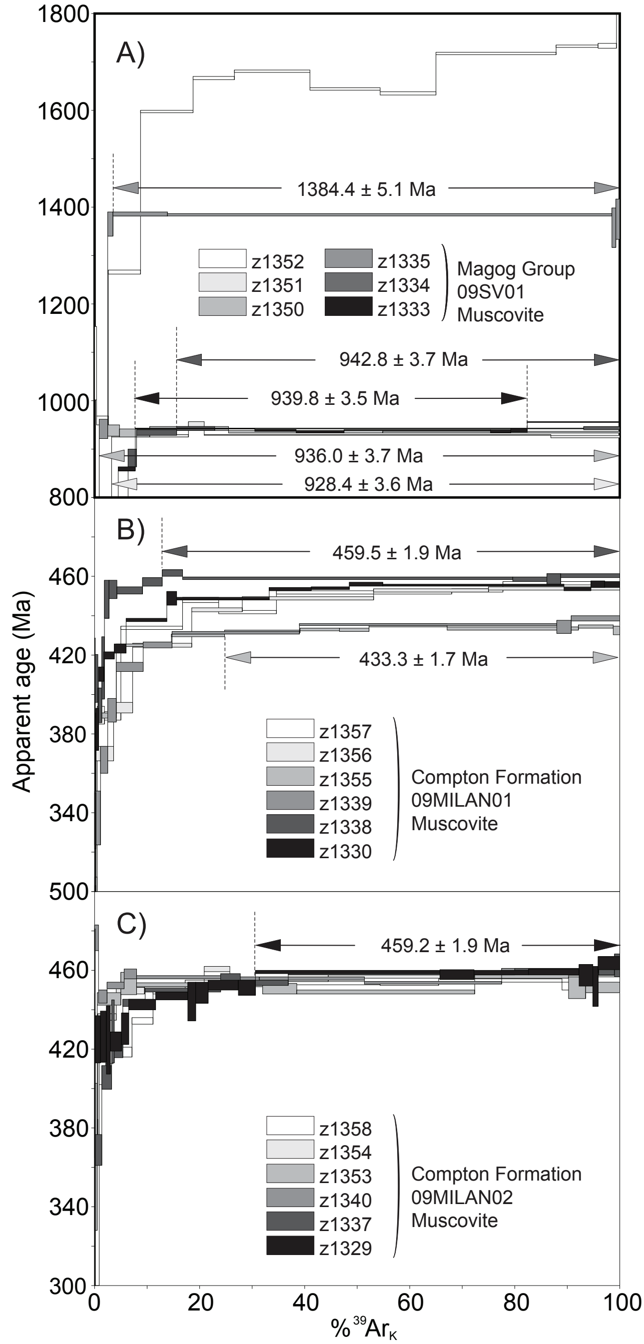


Fig. 7. $^{40}Ar/^{39}Ar$ age spectra for detrital muscovites from (A) the St-Victor Formation—09SV01, and the (B) Milan member of the Compton Formation—09MILAN01 (C)—09MILAN02.

and pelitic fragments embedded in a fine-grained felsic matrix (fig. 9D). In the study area, the Saint-Daniel Mélange is successively overlain by felsic tuff and conglomerate

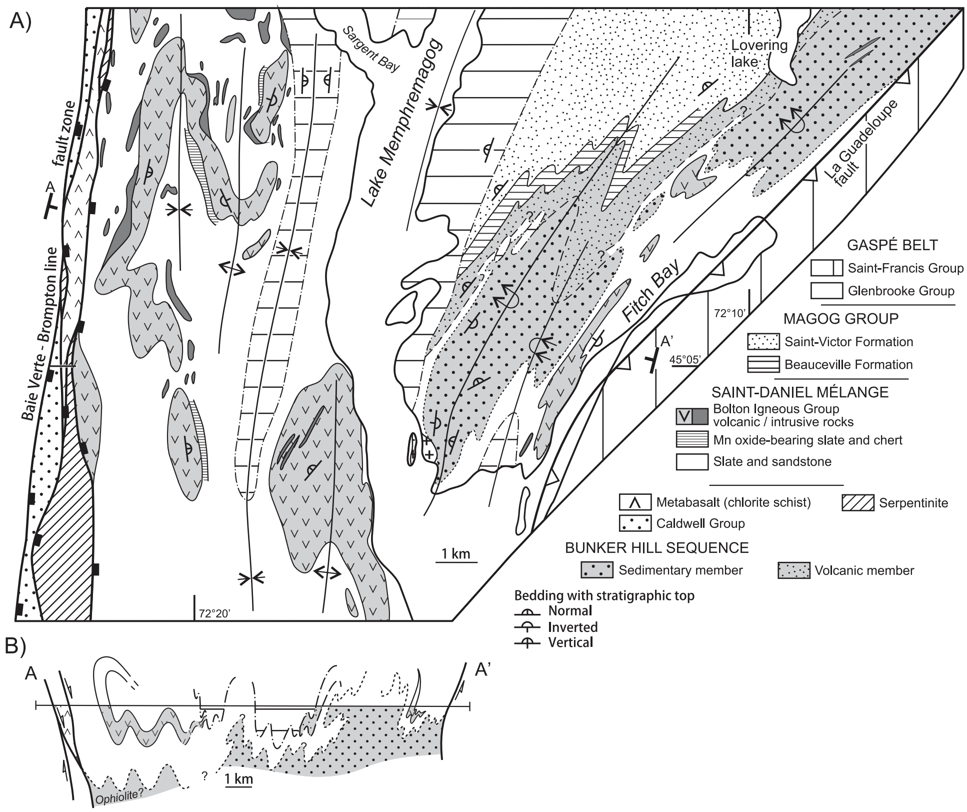


Fig. 8. (A) Detailed geological map and (B) cross-section of the Lake Memphremagog–Fitch Bay area showing stratigraphic relationships between the Saint-Daniel Mélange, Bolton Igneous Group, Bunker Hill sequence and Magog Group. Same symbols for (A) and (B). Symbols for unconformities are as in figure 2. Modified from De Romer (1980), Tremblay (1990) and De Souza (ms, 2012).

of the volcanic member and graphitic pyritiferous black slate of the Beauceville Formation that grades into turbidites of the Saint-Victor Formation (fig. 8).

*U-Pb data.*—Two samples, a coarse-grained feldspathic graywacke (07BUNKER) and a volcanic conglomerate (10BUNKER01), were selected from the sedimentary and volcanic members of the Bunker Hill sequence, respectively, for U-Pb zircon geochronology (fig. 3). A random selection from the sedimentary member zircon grain set was analyzed and yielded sixty-six ages (Appendix 1). The probability density distribution diagram for this data set is rather simple; it shows a discrete peak at 1675 to 1475 Ma and a more prominent one at 1100 to 925 Ma that represents over 77 percent of the analyzed grains (fig. 5A). Most of the remaining analyses are distributed between these two age groups, and a single Ediacaran age of 594 ± 28 Ma was obtained.

Zircon grains that were dated from the volcanic member show a broad Precambrian age distribution with a dominant composite peak in the 925 to 1250 Ma age interval that represents 34 percent of the analyzed grains (fig. 5B). It is also characterized by a very distinct early Paleozoic age population represented by 24 single grain analyses (fig. 5B) that were obtained from euhedral and elongated to prismatic zircon grains with crystal tips showing well-defined oscillatory zoning without clear evidence of inherited cores (fig. 6A). Sixteen analyses from this early Paleozoic population are

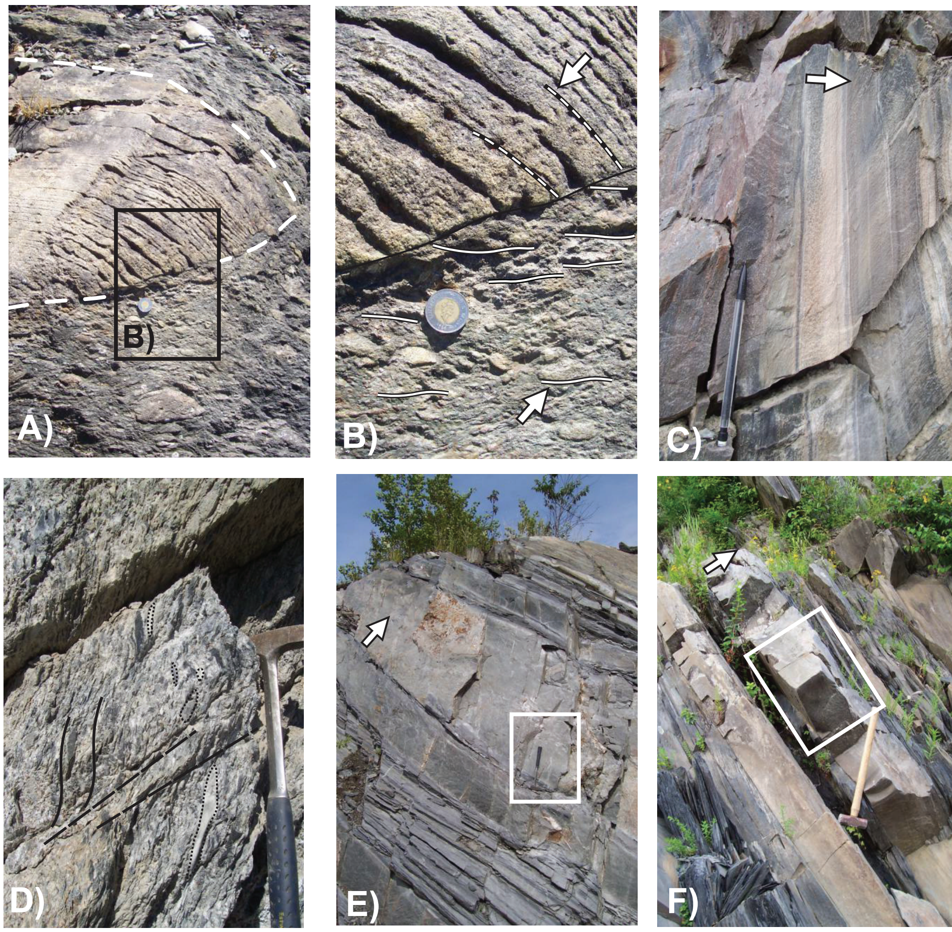


Fig. 9. Field photograph of (A) polymictic conglomerate belonging to the Saint-Daniel Mélange of the Fitch Bay area. The outlined clast is a foliated feldspathic sandstone compositionally similar to the Bunker Hill sequence sedimentary member; (B) detail of (A) showing the sharp contact between the foliated clast and the pebbly matrix. Note that the foliation in the clast (dashed white line) is at high angle to the main foliation ($F_4$) in the matrix (full white line); (C) well-bedded tuff of the Bunker Hill sequence volcanic member. Younging direction is toward the southeast (white arrow); (D) volcanic conglomerate of the Bunker Hill sequence volcanic member that was sampled for U-Pb zircon dating (sample 10BUNKER01). Clasts are highlighted by dotted lines, whereas the full and dashed lines show the trace of the main foliation ($S_4$) and of a superimposed crenulation cleavage, respectively; (E) turbidite outcrop of the Saint-Victor Formation sampled for U-Pb dating of detrital zircons (sample 09SV02); arrow indicates the younging direction (toward the northwest), whereas the white box shows the area of the outcrop that has been sampled; (F) Compton Formation (Milan member) black slate and lithic sandstone; the younging direction is toward the southeast (arrow) and the white box indicates the sampling site of 09MILAN02.

>93 percent concordant and form an age cluster from which was calculated a weighted mean $^{207}Pb/^{206}Pb$ age of 455 ± 6 Ma (inset of fig. 5B).

*The Magog Group*

The lower part of the Magog Group is composed of slate and volcaniclastic rocks attributed to the Beauceville Formation (Slivitzky and St-Julien, 1987), and which have been further subdivided, from base to top, into the Frontière, Etchemin and Beauceville formations in the Beauce area (fig. 4; Cousineau and St-Julien, 1994). The Frontière

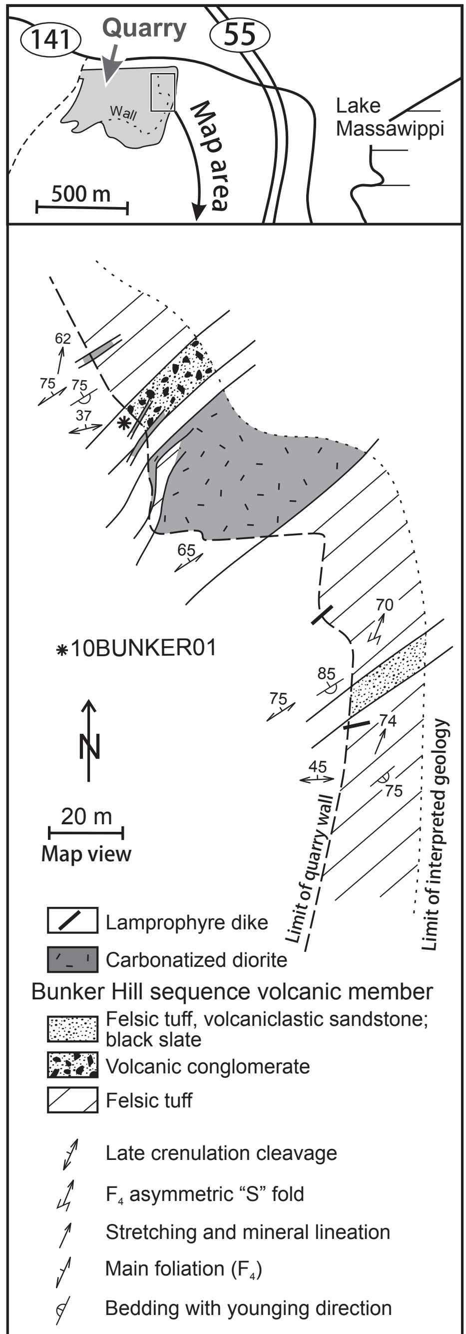


Fig. 10. Sketch map of the location and a section of the Bunker Hill quarry where the volcanic member sample 10BUNKER01 was collected.

Formation consists of interlayered chromite-bearing volcaniclastic sandstone and mudslate, the Etchemin Formation is made up of felsic cherty tuff, whereas the

Beauceville Formation is dominated by graphitic slate and volcaniclastic rocks (Cousineau and St-Julien, 1994). The overlying St-Victor Formation is the most extensive unit of the Magog Group and basically consists of quartz- and lithoclast-rich turbidites (fig. 9E; St-Julien, 1987; Cousineau and St-Julien, 1994).

*U-Pb and $^{40}Ar/^{39}Ar$ data.*—Two samples of coarse-grained lithic sandstone from the Saint-Victor Formation in the Beauce (09SV01) and Lake Memphremagog areas (09SV02; fig. 9E) were selected for detrital zircon U-Pb and muscovite $^{40}$Ar/$^{39}$Ar geochronology. Sample 09SV01 yielded abundant zircon grains of various shapes that suggest igneous and metamorphic sources. Most grains are amber to pinkish and reddish-brown colored, show rounded edges and elliptical to discoid and stubby prismatic shapes. Muscovite grains with a diameter of 0.5 to 1.0 mm were separated from that sample for $^{40}$Ar/$^{39}$Ar analysis. Only a minor amount of zircon grains was recovered from sample 09SV02, which was moreover devoid of detrital muscovite. Separated zircons consisted mostly of clear euhedral grains with smooth to sharp edges and equant to elongated and bipyramidal crystal shapes, but brownish and anhedral to well-rounded grains and crystal fragments were also present. The probability density distribution diagram for the zircon analyses of sample 09SV01 is characterized by a lack of Paleozoic age populations (fig. 5C). It shows distinct peaks in the Neoarchean (2775-2700 Ma) and the late Paleoproterozoic (1900-1850 Ma) and a prominent and broad age group in the 900 to 1400 Ma age interval. This contrasts with the data set acquired from sample 09SV02, for which 41 percent of the dated zircons yielded two Ordovician (480 ± 12 Ma; 459 ± 23 Ma) and thirty-one Silurian to Early Devonian ages (fig. 5D). All of these Paleozoic ages were obtained from euhedral zircons showing oscillatory zoning and lacking well-defined inherited cores (fig. 6B). The remaining analyses from 09SV02 form Neo- to Mesoproterozoic age groups in the 1250 to 1150 Ma and 1100 to 900 Ma intervals, with single grain Paleoproterozoic ages as old as 1900 to 1850 Ma and 1650 to 1600 Ma and Neoproterozoic ages at 675 to 625 Ma. Nine of the analyses yielding Silurian-Early Devonian ages are concordant at *ca.* 90 percent to 105 percent and form an age cluster from which was calculated a weighted mean $^{238}$U/$^{206}$Pb age of 424 ± 6 Ma (inset of fig. 5D).

The $^{40}$Ar/$^{39}$Ar analyses that were performed on muscovite grains from sample 09SV01 yielded five plateau ages, one at *ca.* 1384 (experiment z1335; fig. 7A) and four of them in the *ca.* 943 to 928 Ma age range. A highly-disturbed age spectrum was obtained from experiment z1352, with high- and low-temperature degassing steps suggesting a minimum crystallization age in the Paleoproterozoic (> *ca.* 1730 Ma) and a strong overprint in the Meso- to Neoproterozoic, respectively (fig. 7A).

### *The Compton Formation*

The Compton Formation belongs to the Saint-Francis Group and is described as a succession of alternating sandstone and mudstone (fig. F) formed in a shallow marine deltaic setting and comprising three informal members, the Milan, Lac-Drolet and Saint-Ludger members (Lafrance, ms, 1995; Lavoie, 2004).

*U-Pb and $^{40}Ar/^{39}Ar$ data.*—Two samples, 09MILAN01 and 09MILAN02, were collected from individual beds of Milan member lithic sandstone (see fig. 1 for location of sampling sites). Zircons that were separated from these two samples are of various shapes and colors, varying from well-rounded to prismatic and amber to reddish-brown, and with most grains showing rounded edges. However, euhedral and colorless to light amber colored prismatic to acicular crystals and crystal fragments with sharp edges form a distinct morphological population. Zircon grains were first randomly-selected from both samples. Supplemental grains were carefully handpicked from the euhedral zircon populations to form the 09MILAN01b and 09MILAN02b extra grain sets. Cathodoluminescence imaging of these extra grains has revealed that most show well-defined oscillatory zoning, whereas others are characterized by the presence of inherited cores that are surrounded by oscillatory-zoned overgrowths (figs. 6C and 6D). The detrital zircon probability density distribution plots for samples 09MILAN01 and 09MILAN02 are more-or-less similar, with a very broad Precambrian age population and Paleozoic ages extending into the Devonian, with *ca.* 30 percent and 26 percent of the dated grains corresponding, respectively, to 950 to 1100 Ma and 550 to 375 Ma age intervals (figs. 5E and 5F). The 09MILAN01b and 09MILAN02b extra grain sets also yielded Precambrian to Devonian ages (Appendix 1). All Paleoproterozoic to Early Neoproterozoic ages for the extra grain sets were however obtained from inherited zircon cores (fig. 6C). The youngest ages from the 09MILAN01b extra grain set form a well-defined age cluster in the Early to Middle Devonian that is composed of 13 overlapping concordant (95%-101%) analyses yielding a weighted mean $^{207}Pb/^{206}Pb$ age of 396 ± 5 Ma (inset of fig. 5F). Only few Devonian ages were obtained from the 09MILAN02b extra grain set, but these do not form an age cluster (inset of fig. 5E). As for samples 09MILAN01 and 09MILAN02, both extra grain sets contain varying amounts of Ordovician to Silurian ages, whereas four Ediacaran ages of 614 ± 32 Ma, 596 ± 31, 562 ± 17 and 552 ± 17 Ma were obtained from sample 09MILAN02, including the 09MILAN02b extra grain set.

Samples 09MILAN01 and 09MILAN02 yielded abundant detrital muscovite flakes that were analyzed for $^{40}Ar/^{39}Ar$ dating. Sample 09MILAN01 shows a bimodal age distribution, with four analyses in the Late Ordovician and two in the Silurian. All dated grains, however, show evidence for Ar loss in the low- to medium-temperature steps of the age spectra at *ca.* 375 to 380 Ma, but two analyses yielded well-defined plateau ages at 459.5 ± 1.9 Ma and 433.3 ± 1.7 Ma (fig. 7B). The remaining age spectra for the Late Ordovician and Silurian muscovite age groups show high-temperature steps up to *ca.* 450 to 455 Ma and 435 to 437 Ma, which represent minimum age estimates for the crystallization and/or cooling below the closure temperature of muscovite (fig. 7B). In sample 09MILAN02, one muscovite grain yielded a plateau age at 459.2 ± 1.9 Ma (fig. 7C; muscovite z1329), whereas the remaining analyses show medium- to high-temperature steps in the age spectra that correspond to a *ca.* 450 to 460 Ma interval. Also, experiments z1329 and z1358 show evidence of thermal resetting in the low-temperature steps of the age spectra at *ca.* 420 to 430 Ma (fig. 7C).

## DISCUSSION

Most of the U-Pb detrital zircon ages of this study correspond to major episodes of Appalachian magmatism and/or Laurentian crust formation and amalgamation (fig. 5), and can be separated into three main age groups: 1) Archean (≥2500 Ma), 2) Paleoproterozoic to Neoproterozoic (*ca.* 1900-900 Ma) and 3) Cambrian to Devonian (*ca.* 500-400 Ma). The detrital muscovite $^{40}Ar/^{39}Ar$ results are less heterogeneous (fig. 6), but still suggest the erosion of Precambrian (*ca.* 1730-930 Ma) and Ordovician to Silurian rocks (*ca.* 460-420 Ma).

### *Age, Provenance, and Correlation Interpretations*

*Bunker Hill sequence.*—Although the depositional age of the Bunker Hill sequence sedimentary member remains uncertain, upper and lower age limits can be suggested based on stratigraphic relationships with adjacent rock units and the detrital zircon age data presented herein. For the sedimentary member, the youngest single grain zircon age of 594 ± 29 Ma, the lack of Ordovician or younger detrital zircons and its stratigraphic position relative to the Magog Group grossly constrain its maximum and minimum depositional ages to the Ediacaran and Middle Ordovician periods. Besides, the predominance of Mesoproterozoic zircons and the lack of Archean, Paleoproterozoic and early Paleozoic ages in the Bunker Hill graywacke, combined with the absence of felsic volcanic and/or ophiolitic detritus, are consistent with a derivation mainly from Grenvillian crustal sources.

The composition and tectonic history of the Bunker Hill sedimentary member are rather similar to those of sandstone units of the Humber zone, such as the Caldwell Group, a quartzo-feldspathic sandstone-rich unit belonging to the Neoproterozoic-Early Cambrian rift sequence of Laurentia in southern Quebec (Cousineau, 1990; Bédard and Stevenson, 1998). This is suggested by the sialic composition of the sedimentary member, its detrital zircon population dominated by an almost exclusively Grenvillian component and by structural evidence implying an early phase of folding that pre-dated the deposition of the Saint-Daniel Mélange and Magog Group. Antiformal inliers of Humber zone sandstone units occurring beneath the Dunnage zone have been documented from the Thetford-Mines area (Tremblay and Pinet, 1994; Tremblay and Castonguay, 2002; Schroetter and others, 2005) and represent a structural setting similar to the one proposed for the sedimentary member.

The stratigraphic position of the volcanic member relative to the Magog Group slates and the 455 $\pm$ 6 Ma age yielded by sample 10BUNKER01 suggest that these volcaniclastic rocks were deposited in early Caradocian time. The presence of detrital chromite grains, together with the felsic and calc-alkaline composition of the volcanic member rather indicate that it formed in the vicinity of a volcanic arc and that there were ultramafic rocks in the source area(s). The randomly-selected detrital zircon grain set of sample 10BUNKER01 also supports considerable recycling of Proterozoic to Archean basement rocks and shows a much more broadly defined Precambrian zircon population than for sample 07BUNKER. Although the contribution of a western source component for these volcaniclastic rocks cannot be excluded, a dominant eastern provenance better accounts for their detrital age variations and composition. The Ascot Complex, with its volcanic arc rock assemblage, strong Laurentian inheritance (Tremblay and others, 1989; Tremblay and others, 1994) and local association with mafic-ultramafic rocks (Tremblay, 1992b; Hébert and Labbé, 1997) represents a good source of detritus for the sedimentary member.

The Bunker Hill sequence volcanic member compares well with the chromite-bearing sandstone and felsic tuff of the Frontière and Etchemin formations in the Beauce area (figs. 2 and 4), which have been attributed a Llanvirnian to Caradocian age (Cousineau and St-Julien, 1994). Although that the volcanic member cannot be divided into a sandstone and tuff unit, it consists of a volcanic horizon marking the base of the Magog Group, like the Frontière and Etchemin formations. An almost continuous horizon of undivided volcaniclastic rocks is also present between the Lake Memphremagog and Beauce areas (Slivitzky and St-Julien, 1987) at the same stratigraphic level and most likely represents the continuity of the volcanic member on the northwestern limb of the Saint-Victor synclinorium.

*Magog Group.*—The maximum age limit of the Magog Group is considered to be early Caradocian based on its graptolite fauna (Cousineau and St-Julien, 1994) and a 462 $+5/-4$ Ma zircon age yielded by a felsic tuff of the Beauceville Formation (Marquis and others, 2001). In terms of paleogeographic setting, Cousineau and St-Julien (1994) suggested that the Frontière and Etchemin formations (that is the lowermost stratigraphic units of the Magog Group) were derived mainly from the erosion of a magmatic arc located to the southeast of the Magog basin, and that the Beauceville Formation marks a transition toward northwest-derived continental sources that characterize the Saint-Victor Formation.

Our $^{40}Ar/^{39}Ar$ and U-Pb detrital muscovite and zircon age data for the Saint-Victor Formation bring important new constraints on the age and provenance for the upper part of the Magog Group. The Precambrian detrital zircon and muscovite age distributions for sample 09SV01 are consistent with a derivation from the Grenville and Superior Provinces and possibly from low-grade Taconian nappes of the adjacent Humber zone as recycled sediment, therefore confirming a northwestern source.

Contrastingly, the detrital zircon age distribution for sample 09SV02 shows much less dominant Precambrian source contributions and rather suggests a strong input from Ordovician-Silurian magmatic rocks, most likely from Appalachian arc sources (fig. 5D). The 424 ± 6 Ma weighted mean age that was calculated for the younger zircon grains does not correspond to any known volcanic-plutonic suite in southern Quebec, but possible distal sources, however, include Silurian Piermont Allochthon in western Maine (*ca.* 430-418 Ma; Moench and others, 1995), as well as late Llandoverian volcanic and volcaniclastic rocks occurring in the westernmost part of the Gaspé peninsula (David and Gariépy, 1990; Bourque and others, 2000). Such a Silurian age result for the Magog Group is presently unique but, if correct, indicates that the St-Victor turbidite sequence is possibly as young as Llandoverian-Ludlovian. This would imply, moreover, that the Magog Group represents a 25 to 35 Ma period of more-or-less continuous sedimentation following the accretion of ophiolites and volcanic arcs to the Laurentian margin, as it seems to be the case for correlative sedimentary sequences of the Gaspé Peninsula (Tremblay and others, 1995; Malo, 2004).

*Compton Formation (Saint-Francis Group).*—The Lac Lambton Formation, which forms the base of the Saint-Francis Group, is Pridolian-Early Devonian (Boucot and Drapeau, 1968; Achab and Asselin, 1993; Lavoie and Asselin, 2004), whereas the overlying Ayer's Cliff and Compton formations have yielded Pridolian to Early Devonian chitinozoan and plant fragments (Hueber and others, 1990; van Grootel and others, 1995; Lavoie and Asselin, 2004). The upper age limit of the Saint-Francis Group is not known but it predates the Late Devonian Acadian regional metamorphic imprint (<390-375 Ma; Tremblay and others, 2000) and the emplacement of a series of granitic intrusions that crosscut the Gaspé Belt in southern Quebec (384-374 Ma; Simonetti and Doig, 1990). Further age and provenance interpretations can be proposed by examining our U-Pb and $^{40}Ar/^{39}Ar$ data for the Compton Formation. Samples 09MILAN01 and 09MILAN02 show detrital zircon age distributions that suggest contributions from Archean and Proterozoic Laurentian sources, and from Appalachian Cambrian to Devonian magmatic rocks (figs. 5E and 5F). Neoproterozoic ages obtained from sample 09MILAN02 and its extra grain set, 09MILAN02b, between *ca.* 620 to 550 Ma, overlap with the age interval attributed to Iapetus opening magmatism and peri-Gondwanan Avalonian arcs (figs. 5E and 5F). Conversely, the *ca.* 396 ± 6 Ma weighted mean age calculated for the 09MILAN02b grain set suggests that sedimentation of the Compton Formation has persisted throughout Emsian time.

$^{40}Ar/^{39}Ar$ age data for samples 09MILAN01 and 09MILAN02 can be compared with the tectonic-metamorphic evolution recorded by Cambrian-Ordovician rocks of the Humber zone, (1) the 460 to 450 Ma high-temperature steps and *ca.* 459 Ma plateau ages that characterize both samples correspond to obduction-related regional metamorphism and nappe emplacement, and (2) the *ca.* 433 Ma plateau age and *ca.* 437 to 435 Ma high-temperature steps ages of sample 09MILAN01, as well as the low-temperature thermal overprint shown by sample 09MILAN02 at *ca.* 430 to 420 Ma, can be attributed to the hinterland-directed superposed deformation and related Silurian to Early Devonian metamorphism. This latter metamorphic imprint is recorded only in the low-temperature steps of the muscovite age spectra for sample 09MILAN02, whereas it persists into the medium- to high-temperature steps for sample 09MILAN01, possibly suggesting a deeper exhumation and erosion of the Taconian orogenic wedge for that latter sample. The correlation of detrital muscovite ages from the Compton Formation with the tectonothermal evolution of the internal Humber zone also suggests that Ediacaran zircon ages measured in sample 09MILAN02 can be derived from erosion of rift-related magmatic rocks such as those preserved in Humber zone of southern Quebec (Kumapareli and others, 1989; Hodych and Cox, 2007).

Nevertheless, southeastern-derived peri-Gondwanan sources cannot be firmly excluded.

*Saint-Daniel Mélange and related volcanic rocks.*—The most common and widely represented rock-types in the Saint-Daniel Mélange are interlayered black and green slate, lithic sandstone, dolomitic siltstone and quartzite, and a diagnostic intraformational pebbly mudstone breccia (Schroetter and others, 2006). However, ophiolitic and metamorphic clast-bearing polymictic debris flow breccias and conglomerates commonly occurring towards the base of the Saint-Daniel Mélange have been documented in various areas of southern Quebec and are known to mark an unconformity overlying the ophiolites and, locally, metamorphic sole rocks (Schroetter and others, 2006; De Souza and others, 2008, 2012; De Souza and Tremblay, 2010a). In northern Vermont, the Umbrella Hill Formation consists of debris flow conglomerates found at the base of the Cram Hill Formation (Doolan and others, 1982). It contains abundant quartz vein, metasedimentary and sedimentary rock fragments (Badger, 1979; Doolan and others, 1982), and unconformably overlies previously metamorphosed and deformed rocks assigned to the Humber zone (Doolan and others, 1982). The Umbrella Hill Formation is located at the same stratigraphic position as the Saint-Daniel Mélange polymictic debris flows and both units contain abundant continent-derived clasts (Doolan and others, 1982; Schroetter and others, 2006). We therefore correlate both units as marker horizons of a Taconian unconformity. As previously proposed (Rowley and Kidd, 1981), the lack of well-preserved ophiolites and related rocks beneath this unconformity in northern Vermont, as well as the absence of ophiolite-derived detritus in the Umbrella Hill Formation, suggests that ophiolitic nappes either did not originally extend into northern Vermont or were completely eroded there.

Ordovician (*ca.* 460-463 Ma) volcanic rocks, more-or-less coeval with the Bolton Igneous Group and Ware Volcanics, are also found in the Ascot Complex. Although, the latter has been interpreted as a strongly dismembered volcanic massif (Tremblay and St-Julien, 1990; Tremblay, 1992a), the contact between its volcanic rocks and the overlying sedimentary rocks correlated with those of the Saint-Daniel Mélange and of the Magog Group is locally depositional (Gauthier and others, 1989; Mercier and others, 2012). This relationship suggests that the Ascot Complex forms a volcanic arc basement that was originally overlain by and/or interdigitated with both the Saint-Daniel-type phyllites and the Magog Group siliciclastic sequence. It can also be distinguished from the Bolton Igneous Group and the Ware Volcanics based on the facts that its mafic component shows a wide range of geochemical affinities, varying from mid-ocean ridge basalts, island arc tholeiites and boninitic rocks, and that it is characterized by a unique bimodal composition and the occurrence of a syn-volcanic intrusion. (Tremblay and others, 1989; Hébert and Labbé, 1997).

### *Paleotectonic Evolution*

The isotopic age data and stratigraphic relationships presented above highlight significant differences in the age, provenance and origin of Neoproterozoic(?) to Devonian units of the Saint-Victor synclinorium and the Connecticut Valley–Gaspé trough of southern Quebec. These data can be compared with various geological features of the Quebec-New England Appalachians in order to speculate on the paleotectonic evolution of these terranes. In southern Quebec and western New England, the Taconian orogeny involves the Early to Late Ordovician emplacement of the southern Quebec ophiolites, as well as the formation and accretion of the Shelburne Falls, Ascot Complex and Bronson Hill volcanic arc terranes (Doolan and others, 1982; Stanley and Ratcliffe, 1985; Tremblay, 1992a; Pinet and Tremblay, 1995; Karabinos and others, 1998; Hollocher and others, 2002; Tremblay and Castonguay, 2002). The structural characteristics of the Laurentian margin and the current disposition of ophiolites, mélanges, flysch units and arc volcanics suggest that plate convergence was accommodated by east-dipping (present coordinates) subduction (Osberg, 1978; Rowley and Kidd, 1981; Stanley and Ratcliffe, 1985; Robinson and others, 1998; Moench and Aleinikoff, 2002; Tremblay and Pinet, 2005; Rankin and others, 2007; Tremblay and others, 2011). However, it is presently uncertain if the final closure of Iapetus Ocean proceeded as the result of subduction dipping beneath (van Staal and others, 1998; Rankin and others, 2007) or away from Laurentia (Stanley and Ratcliffe, 1985; Tremblay and Pinet, 2005). The Ordovician to Devonian paleogeographic and tectonic evolution of the Laurentian margin and peri-Laurentian terranes, as deduced from observations and age data presented above, and from previous work in the southern Quebec and New England Appalachians, is illustrated in figure 11 and can be interpreted as follows.

*(1) Taconian obduction and slab breakoff.*—Uprooting and thrusting of oceanic lithosphere toward and then onto the Laurentian margin was initiated at *ca.* 479 to 472 Ma, and continued for a period of approximately 15 M.y., as ophiolitic nappes were progressively translated over the continental margin and uplifted with underlying metamorphic rocks at *ca.* 460 Ma (Tremblay and others, 2011). By *ca.* 460 Ma, ophiolitic and continental metasedimentary rocks thus formed an orogenic wedge that was eroded, probably as a forearc ridge(s) from which detritus was recycled oceanward onto a forearc oceanic basin to form olistostromal and conglomeratic units of the Saint-Daniel Mélange (fig. 11A; Schroetter and others, 2006; Tremblay and others, 2011; De Souza and others, 2012). Erosion and uplift of the amalgamated forearc wedge were however irregular along the strike of the collision zone, with an erosion depth reaching the ophiolitic crustal rocks in Thetford-Mines but cutting much deeper into the exhumed continental margin and the adjacent forearc ridge in the vicinity of the Quebec-Vermont border.

As recorded by the Ascot Complex, arc magmatism along Laurentia was penecontemporeneous with Taconian ophiolite obduction and with the formation of the Bolton Igneous Group, Mount Norris Intrusive Suite and Ware Volcanics. We believed that such widespread magmatism can be reconciled with the introduction of Laurentian continental material into the subduction zone. The subduction (or attempted subduction) of buoyant continental lithosphere is an inherent part of arc-continent collisions and ophiolite emplacement, that frequently leads to crustal contamination of subduction zone magmas and delamination-related breakoff of downgoing slabs, providing a favorable setting for the accelerated uplift of the orogenic wedge and the generation of mafic magmas due to asthenospheric upwelling (Cloos and others, 2005; Dewey, 2005; Afonso and Zlotnik, 2011; Brown and others, 2011). Thermochronological studies (Tremblay and others, 2011; De Souza and others, 2012) and paleotectonic data (Pinet and Tremblay, 1995; De Souza and Tremblay, 2010a) suggest a minimum distance of *ca.* 100 km of underthrusting of the Laurentian margin during the emplacement of the southern Quebec ophiolites. The introduction of subducted sediments into the subduction melting zone may have triggered the formation of abundant felsic magmas (Shimoda and Tatsumi, 1999; Johnson and Plank, 2000; Shimoda and others, 2003), which would then account for the bimodal composition, the inherited crustal signature and strong geochemical variations of supra-subduction zone magmas that characterize the Ascot Complex (fig. 11A; Tremblay and others, 1989; Tremblay and others, 1994; David and Marquis, 1994). Slab breakoff has been already proposed to account for the Mount Norris Intrusive Suite (Kim and others, 2003; Coish, 2010) and a similar mechanism may well be applied to both the Bolton Igneous Group and Ware Volcanics. Collisional delamination resulting in subducting slab breakoff has been documented in New Guinea, where the northern margin of the Australian continent has subducted beneath the Pacific Plate during emplacement of the Irian Ophiolite Belt (Cloos and others, 2005), which fits well as an actualistic model

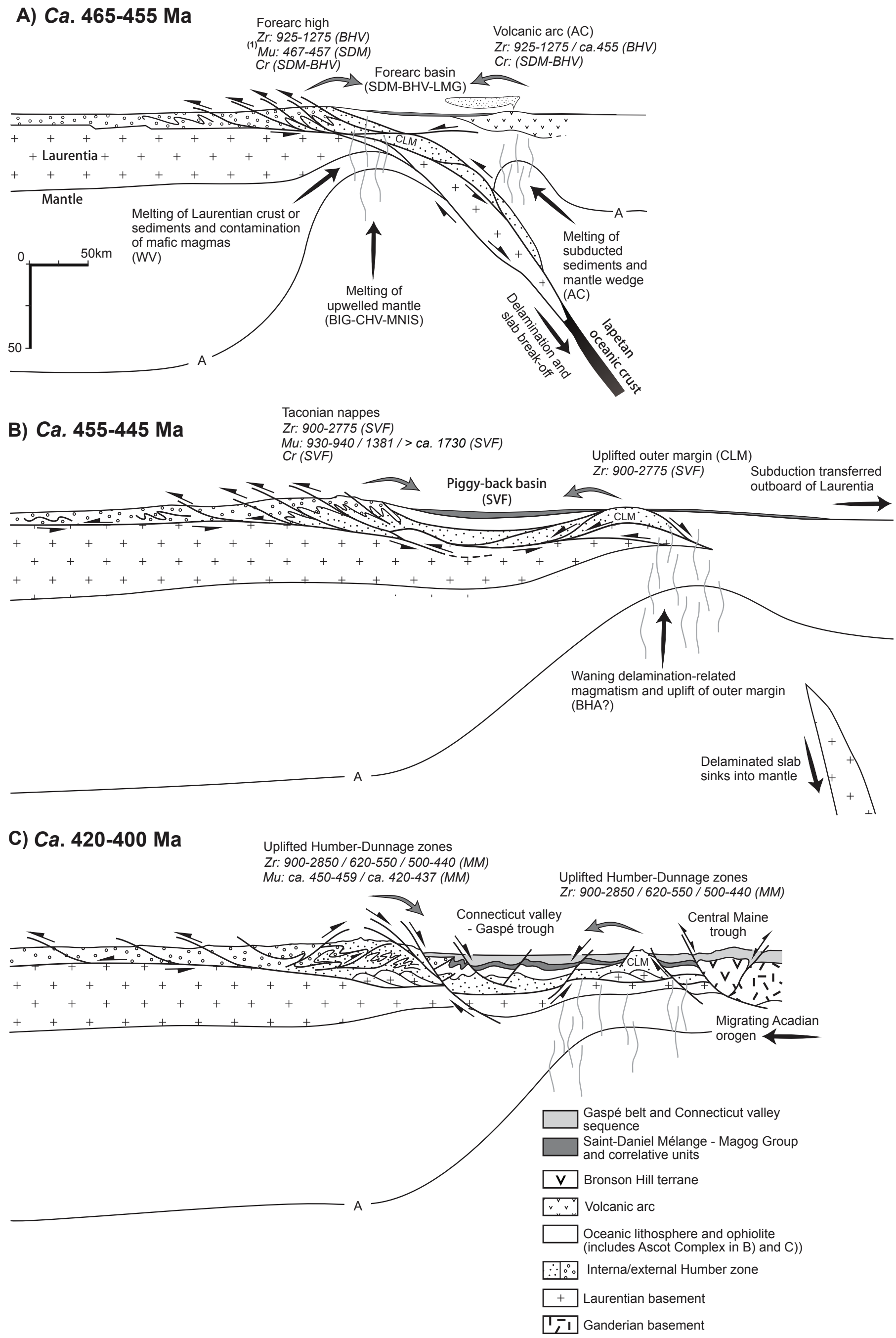


Fig. 11. Schematic model for the tectonostratigraphic evolution of the southern Quebec and northwestern New England Appalachians in Middle Ordovician to Middle Devonian time. Zircon, muscovite and chromite detrital record discussed in this contribution are indicated in italic with their inferred provenance (bold lettering) and host rock unit(s) (acronyms in parentheses). (A) Delamination and breakoff of the subducted Laurentian lithosphere and formation of the Saint-Daniel Mélange, Bolton Igneous Group, Ware Volcanics and lowermost stratigraphic units of the Magog Group in a syn-obduction forearc basin; (B) the delamination of the continental lithosphere is completed and deformation migrates toward the foreland

for the stratigraphic relationships and age data presented herein for southern Quebec and northern Vermont (fig. 11A). As collision proceeded, continued magmatism and erosion of the Ascot Complex volcanic arc resulted in the dispersal of felsic pyroclastic and/or volcaniclastic rocks throughout the forearc region to form the Frontière and Etchemin formations, and the Bunker Hill sequence volcanic member. The Beauceville Formation of the Magog Group was subsequently formed as the forearc basin subsided and the volcanic arc progressively shut down.

*(2) Emplacement of Taconian nappes.*—By 460 to 457 Ma, the obduction of ophiolites *s.s.* was completed and thrusting was transferred within the Humber zone via a foreland-propagating piggy-back thrust system (Tremblay and others, 2011), which was active during most of the Late Ordovician, until *ca.* 445 Ma (St-Julien and Hubert, 1975; Tremblay and Castonguay, 2002; Sasseville and others, 2008). During this time period, detritus shed from the growing thrust nappes of the Humber zone, as well as from ophiolitic and/or chromite-bearing sedimentary rocks were transported into the forearc sedimentary basin, accounting for the detrital zircon and muscovite record measured in the lower part of the Saint-Victor Formation (fig. 11B). It can also be suggested that isostatic rebound, which is expected to follow subduction slab breakoff (Cloos and others, 2005; Afonso and Zotlik, 2011), contributed to the subaerial exposure and erosion of the outer Laurentian margin of Laurentia, part of which is possibly exposed in the Chain Lakes massif (fig. 11B; De Souza and Tremblay, 2010a). As plate convergence resumed following slab breakoff, subduction along Laurentia underwent polarity flip or transferred oceanward toward a new and/or an already existing subduction zone. Late Ordovician-Silurian subduction beneath Laurentia has been suggested previously (Karabinos and others, 1998; Rankin and others, 2007; van Staal, 2007; Dorais and others, 2008, 2012; van Staal and others, 2008) but the lack of clear stratigraphic evidence for an Andean-type margin and related magmatism in the Quebec Appalachians does not favor the polarity flip model (Pinet and Tremblay, 1995; Hollocher and others, 2002; Tremblay and Pinet, 2005).

By late Llandoverian-Wenlockian time, the Gander margin collided with composite Laurentia, a tectonic event that is referred to as the Salinic orogeny in Maritime Canada (Dunning and others, 1990; van Staal, 2007; van Staal and others, 2008), but the polarity of the subduction zone(s) leading to this accretionary event remains speculative (Tremblay and Pinet, 2005; Aleinikoff and others, 2007; Rankin and others, 2007; Wintsch and others, 2007). If our Silurian age for the uppermost part of the Saint-Victor Formation is correct, it would suggest that the Magog Group evolved from a forearc basin in Late Ordovician times, to an intra- or peri-continental sedimentary basin during the Silurian.

*(3) Post-Taconian basin formation.*—Extensional collapse of the Taconian orogen and formation of the Connecticut Valley–Gaspé trough was initiated in Pridolian times in southern Quebec (Tremblay and Pinet, 2005). Silurian to Early Devonian (*ca.* 417-405 Ma; Castonguay and others, 2001, 2007, 2012) normal faulting along the Baie Verte–Brompton line and Saint-Joseph fault in southern Quebec provides a mechanism for basin formation during the Silurian, as well as for the erosion and uplift of the

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Fig. 11 (continued). during formation of the Taconic Allochthons; (C) extensional collapse of the orogen and formation of the Connecticut Valley–Gaspé trough. Note that sketch (A) is scaled with a vertical exaggeration of ~1.5. Dark gray wavy lines underline the inferred ascent of migrating magma. A—asthenosphere-lithoshere boundary; AC—Ascot Complex; BHA—Bronson Hill arc; BIG—Bolton Igneous Group; CHV—Cram Hill volcanics; CLM—Chain Lakes massif; Cr—chromite; BHV—Bunker Hill sequence volcanic member; FEF—Frontière and Etchemin formations; LMG—lower Magog Group; MM—Milan member; MNIS—Mount Norris Intrusive Suite; Mu—muscovite; SDM—Saint-Daniel Mélange; SVF—Saint-Victor Formation; WV—Ware Volcanics; Zr—zircon. (1) Refers to detrital muscovite $^{40}Ar/^{39}Ar$ age data presented by Schroetter and others (2006) and Tremblay and others (2011).

Laurentian margin and accreted rocks of the Humber and Dunnage zones, which account for much of the detrital muscovite and zircon populations found in the Compton Formation (fig. 11C). Sedimentation in the Connecticut Valley–Gaspé trough persisted throughout the Early Devonian and came to an end with the arrival of the Acadian deformation front in the Middle Devonian (Bradley and others, 2000; Bradley and Tucker, 2002; Tremblay and others, 2000).

The detrital zircon and white mica age distributions presented here for southern Québec (fig. 5) is very similar to detrital age results obtained in the South Mayo Trough of western Ireland (Mange and others, 2010; Yin and others, 2012). The South Mayo Trough represents a well-preserved Lower-to-Middle Ordovician forearc to successor basin developed on an arc-continent collision system related to the 475 to 465 Ma Grampian orogeny (Dewey, 2005; Chew and others, 2010), a tectonic event that is considered to be correlative to the Taconian orogeny of the Canadian Appalachians. In the South Mayo Trough, U-Pb detrital zircon ages cluster around three periods of crustal evolution; Archean (>2500 Ma), Mesoproterozoic (2000-1000 Ma), and Early Paleozoic (550-480 Ma), whereas $^{40}Ar/^{39}Ar$ dating of white micas yielded various ages, accordingly with the stratigraphic position of the studied rock units, but spreading over ages as old Paleoproterozoic (*ca.* 2400 Ma) and as young as Middle Ordovician (*ca.* 460 Ma). Tectonically, the South Mayo Trough includes a conformable forearc sequence deposited over an obducting ophiolitic crust/mélange, followed by the development of a synorogenic piggyback basin, and then by an extensional hanging-wall basin developed over exhuming metamorphic rocks of the Grampian orogeny (see Chew and others, 2010). Except for slightly older ages recorded in western Ireland for ophiolite obduction, exhumation, and regional metamorphism of the overthrusted Laurentian margin as compared to southern Québec (that is 10-to-20 Ma; compare Tremblay and others (2011) and Chew and others (2010) for details on the geochronology of theses tectonic events), the paleogeographical and structural model proposed for the South Mayo Trough is very similar to the one we envision for the Dunnage zone and Gaspé Belt sequences of southern Québec and northwestern New England.

## CONCLUSION

In this contribution the stratigraphic evolution of Cambrian-Ordovician volcanic and sedimentary units of the Saint-Victor synclinorium and the northern Vermont part of the Rowe-Hawley belt was synthesized into a revised tectonic model that accounts for along-strike lithostratigraphic variations and the geochronological record of both areas.

During the Taconian orogeny, the final stages of oceanic lithosphere emplacement onto Laurentia gave rise to the formation of a Llanvirn to Caradocian forearc basin. The Saint-Daniel Mélange and correlative units of the Rowe-Hawley belt, and the overlying rocks of the lower Magog Group and Bunker Hill sequence volcanic member were deposited onto a substratum made up of obducted ophiolites and metamorphosed continental margin rocks (for example, the Stowe Formation and the Bunker Hill sequence sedimentary member). The basin accumulated clastic debris shed from uplifted forearc highs of both Cambrian-Ordovician ophiolites and metamorphic rocks, and an outboard volcanic arc represented by the Ascot Complex. This period of syncollisional uplifting was synchronous with the interruption of southeast-directed subduction, as part of the subducted Laurentian margin and/or adjacent pre-Ordovician oceanic lithosphere delaminated and foundered into the mantle. Conformable volcanic flows, and their intrusive counterparts, occurring within the Saint-Daniel Mélange and correlative rocks of northern Vermont, were formed as a result of delamination and related asthenospheric upwelling and melting beneath the collision zone. Tuffs and volcaniclastic rocks of the Bunker Hill sequence volcanic member and lower Magog Group were then deposited unconformably over the Saint-Daniel Mélange as the outboard volcanic arc, represented by the Ascot Complex, was still active but vanishing and was being eroded. Onlapping turbidites of the Saint-Victor Formation record the erosion of the Humber zone thrust nappes as Taconian deformation progressed toward the foreland region. During the Silurian, the extensional collapse of the Taconian orogen resulted in the formation of the Connecticut Valley–Gaspé trough, which accumulated sediment eroded away from uplifted and previously assembled oceanic and continental rocks of Laurentian affinity throughout the Early Devonian. A detrital contribution from accreted peri-Gondwanan terrains is not clear from our data but may have been introduced into the basin during the Early Devonian (Tremblay and Pinet, 2005).

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## Appendix 1

*LA-MC-ICP-MS U-Pb zircon data for rocks of the Ware Volcanics, the Bunker Hill sequence and the Magog and Saint-Francis groups*

| | | | | | | | | | age (Ma) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Grain # | $^{206}Pb$ (cps) | $^{204}Pb$ (cps) | $\frac{^{207}Pb}{^{206}Pb}$ | 2σ | $\frac{^{207}Pb}{^{235}U}$ | 2σ | $\frac{^{206}Pb}{^{238}U}$ | 2σ | $\frac{^{207}Pb}{^{206}Pb}$ | 2σ | $\frac{^{206}Pb}{^{238}U}$ | 2σ | disc. |
| Sample 08M44 - Ware Volcanics | | | | | | | | | | | | | |
| 2 | 52496 | 97 | 0.07602 | 0.00092 | 2.10752 | 0.09427 | 0.20107 | 0.00866 | 1096 | 12 | 1181 | 46 | -8.5 |
| 6 | 38004 | 121 | 0.05775 | 0.00355 | 0.56136 | 0.05094 | 0.07049 | 0.00471 | 520 | 67 | 439 | 28 | 16.2 |
| 8 | 58231 | 111 | 0.05407 | 0.00188 | 0.52722 | 0.02759 | 0.07072 | 0.00277 | 374 | 39 | 440 | 17 | -18.4 |
| 9 | 52264 | 77 | 0.06737 | 0.00154 | 1.37250 | 0.08339 | 0.14775 | 0.00832 | 849 | 24 | 888 | 47 | -4.9 |
| 11 | 44126 | 86 | 0.06521 | 0.00134 | 1.37901 | 0.08238 | 0.15338 | 0.00860 | 781 | 22 | 920 | 48 | -19.1 |
| 12 | 58220 | 92 | 0.06818 | 0.00086 | 1.44336 | 0.05385 | 0.15353 | 0.00539 | 874 | 13 | 921 | 30 | -5.7 |
| 13 | 130259 | 98 | 0.07171 | 0.00061 | 1.51105 | 0.06377 | 0.15282 | 0.00632 | 978 | 9 | 917 | 35 | 6.7 |
| 16 | 34261 | 97 | 0.06349 | 0.00185 | 1.33099 | 0.07306 | 0.15204 | 0.00707 | 725 | 31 | 912 | 39 | -27.8 |
| 17 | 82019 | 119 | 0.07112 | 0.00094 | 1.49510 | 0.09281 | 0.15247 | 0.00925 | 961 | 14 | 915 | 52 | 5.1 |
| 24 | 93815 | 28 | 0.06772 | 0.00063 | 1.27177 | 0.05898 | 0.13621 | 0.00619 | 860 | 10 | 823 | 35 | 4.6 |
| 29 | 109446 | 43 | 0.08977 | 0.00136 | 2.60019 | 0.12855 | 0.21007 | 0.00988 | 1421 | 14 | 1229 | 52 | 14.8 |
| 32 | 135576 | 49 | 0.09025 | 0.00075 | 2.58533 | 0.16458 | 0.20777 | 0.01311 | 1431 | 8 | 1217 | 70 | 16.4 |
| 33 | 142949 | 44 | 0.09879 | 0.00075 | 3.41858 | 0.14896 | 0.25096 | 0.01077 | 1601 | 7 | 1443 | 55 | 11.0 |
| 34 | 201780 | 85 | 0.07253 | 0.00057 | 1.48536 | 0.06436 | 0.14853 | 0.00633 | 1001 | 8 | 893 | 35 | 11.6 |
| 35 | 45717 | 76 | 0.07414 | 0.00220 | 1.97235 | 0.1117 | 0.19295 | 0.00931 | 1045 | 30 | 1137 | 50 | -9.6 |
| 36 | 71036 | 83 | 0.06796 | 0.00105 | 1.39619 | 0.07878 | 0.14900 | 0.00809 | 867 | 16 | 895 | 45 | -3.5 |
| 38 | 125785 | 81 | 0.07149 | 0.00051 | 1.44714 | 0.05538 | 0.14680 | 0.00552 | 972 | 7 | 883 | 31 | 9.8 |
| 39 | 67221 | 54 | 0.07556 | 0.00091 | 1.86283 | 0.08306 | 0.17880 | 0.00768 | 1084 | 12 | 1060 | 42 | 2.3 |
| 40 | 84942 | 92 | 0.06847 | 0.00115 | 1.44885 | 0.05852 | 0.15346 | 0.00564 | 883 | 17 | 920 | 31 | -4.6 |
| 41 | 90181 | 90 | 0.06715 | 0.00070 | 1.37228 | 0.05353 | 0.14822 | 0.00557 | 842 | 11 | 891 | 31 | -6.2 |
| 42 | 116498 | 109 | 0.06855 | 0.00078 | 1.35895 | 0.07208 | 0.14377 | 0.00745 | 885 | 12 | 866 | 42 | 2.3 |
| 43 | 38461 | 139 | 0.06320 | 0.00279 | 1.31451 | 0.0867 | 0.15084 | 0.00739 | 715 | 47 | 906 | 41 | -28.6 |
| 48 | 63186 | 117 | 0.06865 | 0.00094 | 1.52888 | 0.06735 | 0.16152 | 0.00676 | 888 | 14 | 965 | 37 | -9.3 |
| 51 | 31817 | 155 | 0.08627 | 0.00162 | 3.35040 | 0.14649 | 0.27198 | 0.01121 | 1344 | 18 | 1551 | 57 | -17.3 |
| 52 | 144373 | 152 | 0.05723 | 0.00052 | 0.72321 | 0.03592 | 0.09165 | 0.00448 | 500 | 10 | 565 | 26 | -13.5 |
| Sample 07BUNKER - Bunker Hill sequence - sedimentary member | | | | | | | | | | | | | |
| 2 | 99704 | 24 | 0.06628 | 0.00267 | 1.58618 | 0.09892 | 0.17357 | 0.00827 | 815 | 42 | 1032 | 45 | -28.8 |
| 3 | 124729 | 22 | 0.06864 | 0.00278 | 1.74466 | 0.1061 | 0.18434 | 0.00836 | 888 | 42 | 1091 | 45 | -24.8 |
| 4 | 322275 | 34 | 0.07302 | 0.00287 | 1.94204 | 0.11962 | 0.19289 | 0.00914 | 1014 | 40 | 1137 | 49 | -13.2 |
| 9 | 109696 | 16 | 0.06949 | 0.00286 | 1.74434 | 0.12658 | 0.18206 | 0.01088 | 913 | 42 | 1078 | 59 | -19.6 |
| 10 | 206360 | 14 | 0.07046 | 0.00281 | 1.70463 | 0.10168 | 0.17546 | 0.00779 | 942 | 41 | 1042 | 43 | -11.5 |
| 11 | 68189 | 111 | 0.07283 | 0.00293 | 1.87212 | 0.1226 | 0.18642 | 0.00963 | 1009 | 41 | 1102 | 52 | -10.0 |
| 12 | 358057 | 92 | 0.10026 | 0.00393 | 4.03051 | 0.25775 | 0.29155 | 0.01473 | 1629 | 36 | 1649 | 73 | -1.4 |
| 13 | 98418 | 69 | 0.07196 | 0.00284 | 1.72040 | 0.09766 | 0.17340 | 0.00707 | 985 | 40 | 1031 | 39 | -5.1 |
| 15 | 122013 | 83 | 0.07406 | 0.00292 | 1.88111 | 0.10817 | 0.18422 | 0.00771 | 1043 | 40 | 1090 | 42 | -4.9 |
| 16 | 135728 | 60 | 0.07294 | 0.00287 | 1.78741 | 0.10790 | 0.17772 | 0.00813 | 1012 | 40 | 1055 | 44 | -4.5 |
| 17 | 22703 | 17 | 0.07252 | 0.00296 | 1.94373 | 0.12269 | 0.19440 | 0.00936 | 1001 | 41 | 1145 | 50 | -15.8 |
| 18 | 245700 | 39 | 0.07431 | 0.00292 | 1.84225 | 0.10581 | 0.17980 | 0.00752 | 1050 | 40 | 1066 | 41 | -1.7 |
| 19 | 22072 | 31 | 0.09548 | 0.00387 | 3.81096 | 0.26479 | 0.28950 | 0.01634 | 1537 | 38 | 1639 | 81 | -7.5 |
| 20 | 194897 | 37 | 0.07504 | 0.00295 | 1.89670 | 0.11206 | 0.18331 | 0.00808 | 1070 | 40 | 1085 | 44 | -1.6 |
| 20 | 30189 | 113 | 0.06975 | 0.00287 | 1.72318 | 0.10466 | 0.17919 | 0.00801 | 921 | 42 | 1063 | 44 | -16.7 |
| 22 | 48907 | 103 | 0.06799 | 0.00272 | 1.47054 | 0.08851 | 0.15686 | 0.00706 | 868 | 41 | 939 | 39 | -8.8 |
| 23 | 74877 | 104 | 0.05751 | 0.00230 | 0.76517 | 0.04898 | 0.09649 | 0.00482 | 511 | 44 | 594 | 28 | -16.9 |
| 24 | 495141 | 117 | 0.09329 | 0.00366 | 3.30010 | 0.20918 | 0.25657 | 0.01278 | 1494 | 37 | 1472 | 65 | 1.6 |
| 25 | 103911 | 104 | 0.08039 | 0.00318 | 2.32639 | 0.14859 | 0.20988 | 0.01053 | 1207 | 39 | 1228 | 56 | -2.0 |
| 26 | 137849 | 94 | 0.07169 | 0.00283 | 1.65517 | 0.10418 | 0.16744 | 0.00821 | 977 | 40 | 998 | 45 | -2.3 |
| 27 | 50101 | 72 | 0.07077 | 0.00289 | 1.73268 | 0.10163 | 0.17756 | 0.00748 | 951 | 42 | 1054 | 41 | -11.7 |
| 28 | 186909 | 92 | 0.07118 | 0.00280 | 1.58577 | 0.09903 | 0.16158 | 0.00783 | 963 | 40 | 966 | 43 | -0.3 |
| 29 | 133576 | 88 | 0.07360 | 0.00290 | 1.87156 | 0.11059 | 0.18442 | 0.00811 | 1031 | 40 | 1091 | 44 | -6.4 |
| 30 | 187226 | 94 | 0.07012 | 0.00277 | 1.58599 | 0.08991 | 0.16405 | 0.00668 | 932 | 40 | 979 | 37 | -5.5 |
| 31 | 149808 | 107 | 0.09931 | 0.00391 | 3.87399 | 0.23034 | 0.28291 | 0.01261 | 1611 | 37 | 1606 | 63 | 0.4 |
| 32 | 32004 | 106 | 0.07107 | 0.00297 | 1.70976 | 0.10787 | 0.17447 | 0.00824 | 960 | 43 | 1037 | 45 | -8.7 |
| 33 | 38176 | 86 | 0.06691 | 0.00281 | 1.46343 | 0.08583 | 0.15863 | 0.00650 | 835 | 44 | 949 | 36 | -14.7 |
| 34 | 1563568 | 81 | 0.09483 | 0.00372 | 3.49485 | 0.20725 | 0.26728 | 0.01190 | 1525 | 37 | 1527 | 60 | -0.2 |
| 37 | 51508 | 80 | 0.07234 | 0.00288 | 1.79266 | 0.10294 | 0.17973 | 0.00744 | 995 | 40 | 1066 | 41 | -7.6 |
| 38 | 784114 | 91 | 0.10176 | 0.00399 | 4.08197 | 0.24738 | 0.29094 | 0.01345 | 1656 | 36 | 1646 | 67 | 0.7 |
| 39 | 401423 | 79 | 0.07290 | 0.00286 | 1.71216 | 0.10009 | 0.17034 | 0.00737 | 1011 | 40 | 1014 | 40 | -0.3 |
| 40 | 538790 | 86 | 0.07262 | 0.00285 | 1.66712 | 0.09592 | 0.16650 | 0.00701 | 1003 | 40 | 993 | 39 | 1.1 |
| 41 | 223186 | 41 | 0.09985 | 0.00393 | 3.84670 | 0.21842 | 0.27940 | 0.01145 | 1621 | 37 | 1588 | 57 | 2.3 |
| 44 | 36722 | 69 | 0.06652 | 0.00278 | 1.52898 | 0.09133 | 0.16670 | 0.00712 | 823 | 44 | 994 | 39 | -22.4 |
| 45 | 100937 | 62 | 0.09793 | 0.00389 | 3.76865 | 0.23523 | 0.27910 | 0.01344 | 1585 | 37 | 1587 | 67 | -0.1 |
| 46 | 92153 | 0 | 0.07210 | 0.00285 | 1.80411 | 0.09866 | 0.18148 | 0.00685 | 989 | 40 | 1075 | 37 | -9.5 |
| 47 | 102635 | 0 | 0.07358 | 0.00291 | 1.91839 | 0.11339 | 0.18909 | 0.00831 | 1030 | 40 | 1116 | 45 | -9.1 |
| 48 | 150009 | 0 | 0.07306 | 0.00289 | 1.81036 | 0.10618 | 0.17972 | 0.00777 | 1016 | 40 | 1065 | 42 | -5.3 |
| 51 | 322463 | 11 | 0.07346 | 0.00262 | 1.88341 | 0.13551 | 0.18595 | 0.01162 | 1027 | 36 | 1099 | 63 | -7.7 |
| 52 | 68390 | 4 | 0.06765 | 0.00258 | 1.67250 | 0.12586 | 0.17932 | 0.01163 | 858 | 40 | 1063 | 63 | -26.0 |
| 53 | 78836 | 5 | 0.09563 | 0.00349 | 3.87451 | 0.28559 | 0.29386 | 0.01881 | 1540 | 34 | 1661 | 93 | -8.9 |
| 54 | 283254 | 2 | 0.08696 | 0.00311 | 2.89586 | 0.21093 | 0.24151 | 0.01532 | 1360 | 34 | 1395 | 79 | -2.9 |
| 55 | 132133 | 2 | 0.07121 | 0.00258 | 1.81773 | 0.14373 | 0.18513 | 0.01301 | 963 | 37 | 1095 | 70 | -14.8 |
| 56 | 113929 | 4 | 0.07121 | 0.00259 | 1.73321 | 0.12831 | 0.17654 | 0.01139 | 963 | 37 | 1048 | 62 | -9.5 |
| 57 | 82560 | 5 | 0.06611 | 0.00254 | 1.53266 | 0.12400 | 0.16813 | 0.01197 | 810 | 40 | 1002 | 66 | -25.6 |
| 59 | 101127 | 4 | 0.06760 | 0.00246 | 1.54055 | 0.11328 | 0.16528 | 0.01056 | 856 | 38 | 986 | 58 | -16.3 |
| 60 | 175788 | 7 | 0.07235 | 0.00260 | 1.75529 | 0.13067 | 0.17595 | 0.01147 | 996 | 37 | 1045 | 63 | -5.3 |

Appendix 1

*(continued)*

| Grain # | $^{206}Pb$ (cps) | $^{204}Pb$ (cps) | $\frac{^{207}Pb}{^{206}Pb}$ | 2σ | $\frac{^{207}Pb}{^{235}U}$ | 2σ | $\frac{^{206}Pb}{^{238}U}$ | 2σ | age (Ma) $\frac{^{207}Pb}{^{206}Pb}$ | 2σ | age (Ma) $\frac{^{206}Pb}{^{238}U}$ | 2σ | disc. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample 07BUNKER - Bunker Hill sequence - sedimentary member | | | | | | | | | | | | | |
| 61 | 152116 | 40 | 0.07061 | 0.00257 | 1.70667 | 0.12708 | 0.17529 | 0.01139 | 946 | 37 | 1041 | 62 | -10.9 |
| 62 | 196262 | 33 | 0.07181 | 0.00257 | 1.74035 | 0.12636 | 0.17576 | 0.01110 | 981 | 36 | 1044 | 61 | -7.0 |
| 63 | 774670 | 34 | 0.07324 | 0.00261 | 1.80165 | 0.13643 | 0.17841 | 0.01192 | 1021 | 36 | 1058 | 65 | -4.0 |
| 64 | 244025 | 159 | 0.07758 | 0.00395 | 1.98416 | 0.16851 | 0.18550 | 0.01262 | 1136 | 51 | 1097 | 68 | 3.7 |
| 65 | 239115 | 14 | 0.07349 | 0.00263 | 1.76788 | 0.13772 | 0.17447 | 0.01207 | 1028 | 36 | 1037 | 66 | -1.0 |
| 68 | 229769 | 8 | 0.08049 | 0.00288 | 2.30399 | 0.17017 | 0.20761 | 0.01341 | 1209 | 35 | 1216 | 71 | -0.6 |
| 69 | 328778 | 1 | 0.07253 | 0.00259 | 1.68981 | 0.11939 | 0.16897 | 0.01030 | 1001 | 36 | 1006 | 57 | -0.6 |
| 70 | 271656 | 5 | 0.07147 | 0.00257 | 1.62751 | 0.11704 | 0.16516 | 0.01028 | 971 | 37 | 985 | 57 | -1.6 |
| 71 | 85121 | 85 | 0.06581 | 0.00246 | 1.42143 | 0.10329 | 0.15665 | 0.00976 | 800 | 39 | 938 | 54 | -18.5 |
| 73 | 104082 | 47 | 0.06687 | 0.00249 | 1.46505 | 0.10720 | 0.15889 | 0.01001 | 834 | 39 | 951 | 55 | -15.1 |
| 75 | 152947 | 72 | 0.07188 | 0.00263 | 1.63730 | 0.12418 | 0.16521 | 0.01098 | 982 | 37 | 986 | 60 | -0.4 |
| 76 | 146049 | 60 | 0.07244 | 0.00262 | 1.75297 | 0.12979 | 0.17550 | 0.01134 | 998 | 37 | 1042 | 62 | -4.8 |
| 78 | 61251 | 51 | 0.06575 | 0.00265 | 1.53737 | 0.11493 | 0.16959 | 0.01067 | 798 | 42 | 1010 | 59 | -28.6 |
| 79 | 154058 | 76 | 0.06797 | 0.00248 | 1.46927 | 0.11083 | 0.15679 | 0.01036 | 867 | 38 | 939 | 57 | -8.8 |
| 80 | 67017 | 67 | 0.06729 | 0.00249 | 1.60364 | 0.11371 | 0.17285 | 0.01046 | 847 | 38 | 1028 | 57 | -23.2 |
| 83 | 716296 | 83 | 0.07375 | 0.00263 | 1.71064 | 0.12506 | 0.16823 | 0.01074 | 1035 | 36 | 1002 | 59 | 3.4 |
| 84 | 196199 | 75 | 0.06974 | 0.00252 | 1.59746 | 0.11311 | 0.16614 | 0.01011 | 921 | 37 | 991 | 56 | -8.2 |
| 85 | 433166 | 99 | 0.07343 | 0.00262 | 1.81122 | 0.12588 | 0.17890 | 0.01067 | 1026 | 36 | 1061 | 58 | -3.7 |
| 86 | 433307 | 100 | 0.09415 | 0.00336 | 3.52816 | 0.26159 | 0.27179 | 0.01766 | 1511 | 34 | 1550 | 89 | -2.9 |
| Sample 10BUNKER01 - Bunker Hill sequence volcanic member | | | | | | | | | | | | | |
| 1 | 99493 | 198 | 0.05698 | 0.00235 | 0.56998 | 0.03447 | 0.07255 | 0.00321 | 491 | 91 | 452 | 19 | 8.3 |
| 2 | 56279 | 41 | 0.05930 | 0.00101 | 0.57787 | 0.04647 | 0.07068 | 0.00556 | 578 | 37 | 440 | 33 | 24.6 |
| 3 | 78807 | 21 | 0.05619 | 0.00064 | 0.56614 | 0.02628 | 0.07307 | 0.00329 | 460 | 25 | 455 | 20 | 1.2 |
| 4 | 36488 | 47 | 0.07757 | 0.00163 | 1.64337 | 0.12563 | 0.15366 | 0.01129 | 1136 | 21 | 921 | 63 | 20.2 |
| 5 | 24795 | 46 | 0.08080 | 0.00222 | 1.83804 | 0.14608 | 0.16498 | 0.01231 | 1217 | 27 | 984 | 68 | 20.6 |
| 6 | 28701 | 83 | 0.08150 | 0.00188 | 1.95648 | 0.13412 | 0.17412 | 0.01124 | 1233 | 23 | 1035 | 61 | 17.4 |
| 7 | 135961 | 48 | 0.05640 | 0.00071 | 0.55233 | 0.02320 | 0.07102 | 0.00285 | 468 | 28 | 442 | 17 | 5.7 |
| 8 | 54834 | 57 | 0.05615 | 0.00098 | 0.55480 | 0.02457 | 0.07166 | 0.00292 | 458 | 39 | 446 | 18 | 3 |
| 9 | 66949 | 29 | 0.05602 | 0.00064 | 0.54477 | 0.02229 | 0.07053 | 0.00277 | 453 | 25 | 439 | 17 | 3 |
| 10 | 14374 | 51 | 0.09330 | 0.00485 | 2.48285 | 0.20981 | 0.19300 | 0.01285 | 1494 | 49 | 1138 | 69 | 26 |
| 11 | 124688 | 66 | 0.05910 | 0.00129 | 0.57095 | 0.02876 | 0.07006 | 0.00318 | 571 | 47 | 437 | 19 | 24 |
| 12 | 40287 | 125 | 0.06083 | 0.00117 | 0.63037 | 0.04016 | 0.07516 | 0.00457 | 633 | 21 | 467 | 27 | 27 |
| 13 | 132180 | 39 | 0.05635 | 0.00056 | 0.55761 | 0.02316 | 0.07177 | 0.00290 | 466 | 22 | 447 | 17 | 4 |
| 14 | 119354 | 27 | 0.05594 | 0.00060 | 0.54403 | 0.02145 | 0.07054 | 0.00268 | 450 | 24 | 439 | 16 | 2 |
| 15 | 115299 | 52 | 0.05626 | 0.00060 | 0.53869 | 0.02213 | 0.06945 | 0.00275 | 462 | 24 | 433 | 17 | 7 |
| 16 | 86256 | 159 | 0.07592 | 0.00127 | 1.74749 | 0.15173 | 0.16695 | 0.01422 | 1093 | 17 | 995 | 78 | 10 |
| 17 | 80057 | 86 | 0.06035 | 0.00199 | 0.60395 | 0.03053 | 0.07259 | 0.00278 | 616 | 71 | 452 | 17 | 28 |
| 18 | 156912 | 168 | 0.18209 | 0.00264 | 12.70663 | 0.95792 | 0.50611 | 0.03744 | 2672 | 12 | 2640 | 158 | 1 |
| 20 | 124807 | 51 | 0.05601 | 0.00064 | 0.54070 | 0.02102 | 0.07001 | 0.00260 | 453 | 25 | 436 | 16 | 4 |
| 21 | 92635 | 56 | 0.05608 | 0.00061 | 0.54269 | 0.02291 | 0.07019 | 0.00286 | 455 | 24 | 437 | 17 | 4 |
| 22 | 128849 | 39 | 0.05568 | 0.00061 | 0.53583 | 0.02105 | 0.06980 | 0.00263 | 439 | 24 | 435 | 16 | 1 |
| 23 | 133266 | 59 | 0.05714 | 0.00088 | 0.55853 | 0.02409 | 0.07090 | 0.00286 | 497 | 34 | 442 | 17 | 12 |
| 24 | 104891 | 38 | 0.05566 | 0.00057 | 0.53661 | 0.02306 | 0.06992 | 0.00292 | 439 | 23 | 436 | 18 | 1 |
| 25 | 154277 | 53 | 0.05640 | 0.00065 | 0.54963 | 0.02275 | 0.07067 | 0.00281 | 468 | 26 | 440 | 17 | 6 |
| 26 | 174459 | 93 | 0.05596 | 0.00072 | 0.53077 | 0.02182 | 0.06879 | 0.00269 | 451 | 29 | 429 | 16 | 5 |
| 27 | 115874 | 87 | 0.05714 | 0.00091 | 0.56157 | 0.02343 | 0.07128 | 0.00275 | 497 | 35 | 444 | 17 | 11 |
| 28 | 63863 | 54 | 0.05597 | 0.00075 | 0.53300 | 0.02184 | 0.06907 | 0.00268 | 451 | 30 | 431 | 16 | 5 |
| 29 | 39738 | 5 | 0.08611 | 0.00223 | 1.99796 | 0.13819 | 0.16829 | 0.01079 | 1341 | 25 | 1003 | 59 | 27 |
| 31 | 82248 | 0 | 0.07764 | 0.00132 | 1.76770 | 0.11223 | 0.16513 | 0.01010 | 1138 | 17 | 985 | 56 | 14 |
| 33 | 57170 | 1 | 0.07749 | 0.00150 | 1.55280 | 0.10238 | 0.14532 | 0.00916 | 1134 | 19 | 875 | 51 | 24 |
| 34 | 60956 | 1 | 0.18684 | 0.00280 | 12.21891 | 0.77421 | 0.47432 | 0.02920 | 2715 | 12 | 2502 | 126 | 9 |
| 36 | 153071 | 1 | 0.09016 | 0.00136 | 2.85038 | 0.18722 | 0.22930 | 0.01466 | 1429 | 14 | 1331 | 76 | 8 |
| 37 | 178208 | 75 | 0.05600 | 0.00058 | 0.55899 | 0.02213 | 0.07239 | 0.00277 | 453 | 23 | 451 | 17 | 0 |
| 38 | 80563 | 69 | 0.05721 | 0.00097 | 0.57284 | 0.02674 | 0.07262 | 0.00316 | 500 | 37 | 452 | 19 | 10 |
| 40 | 175711 | 0 | 0.07428 | 0.00115 | 1.47951 | 0.11682 | 0.14446 | 0.01119 | 1049 | 16 | 870 | 63 | 18 |
| 41 | 39701 | 176 | 0.08301 | 0.00153 | 1.81761 | 0.12828 | 0.15880 | 0.01082 | 1269 | 18 | 950 | 60 | 27 |
| 42 | 71474 | 198 | 0.07833 | 0.00132 | 1.68128 | 0.13418 | 0.15566 | 0.01214 | 1155 | 17 | 933 | 67 | 21 |
| 43 | 219264 | 145 | 0.07397 | 0.00112 | 1.59492 | 0.11082 | 0.15638 | 0.01060 | 1041 | 15 | 937 | 59 | 11 |
| 44 | 216658 | 149 | 0.09632 | 0.00148 | 3.13815 | 0.20345 | 0.23630 | 0.01489 | 1554 | 14 | 1367 | 77 | 13 |
| 45 | 81213 | 144 | 0.07721 | 0.00138 | 1.58462 | 0.09468 | 0.14886 | 0.00848 | 1127 | 18 | 895 | 47 | 22 |
| 46 | 79910 | 144 | 0.07917 | 0.00133 | 1.77596 | 0.12314 | 0.16269 | 0.01094 | 1176 | 17 | 972 | 60 | 19 |
| 47 | 52136 | 66 | 0.05594 | 0.00071 | 0.51963 | 0.02107 | 0.06737 | 0.00260 | 450 | 28 | 420 | 16 | 7 |
| 48 | 102968 | 169 | 0.10236 | 0.00160 | 3.70937 | 0.25383 | 0.26282 | 0.01751 | 1667 | 14 | 1504 | 89 | 11 |
| 49 | 43018 | 137 | 0.09255 | 0.00208 | 2.52148 | 0.18487 | 0.19760 | 0.01379 | 1479 | 21 | 1162 | 74 | 23 |
| 51 | 40722 | 153 | 0.08573 | 0.00189 | 1.93671 | 0.12817 | 0.16384 | 0.01023 | 1332 | 21 | 978 | 56 | 29 |
| 52 | 104235 | 183 | 0.07652 | 0.00131 | 1.75146 | 0.13554 | 0.16601 | 0.01253 | 1109 | 17 | 990 | 69 | 12 |
| 53 | 29839 | 161 | 0.10835 | 0.00244 | 3.73492 | 0.28779 | 0.25001 | 0.01842 | 1772 | 21 | 1439 | 94 | 21 |
| 54 | 76966 | 179 | 0.09359 | 0.00154 | 2.93601 | 0.20794 | 0.22753 | 0.01567 | 1500 | 16 | 1322 | 82 | 13 |
| 55 | 17897 | 150 | 0.10723 | 0.00315 | 3.35864 | 0.26186 | 0.22717 | 0.01641 | 1753 | 27 | 1320 | 86 | 27 |
| 58 | 138618 | 84 | 0.09052 | 0.00136 | 2.73943 | 0.16626 | 0.21949 | 0.01291 | 1437 | 14 | 1279 | 68 | 12 |
| 60 | 57661 | 99 | 0.08041 | 0.00154 | 1.81690 | 0.12300 | 0.16387 | 0.01064 | 1207 | 19 | 978 | 59 | 20 |
| 61 | 107731 | 161 | 0.07600 | 0.00167 | 1.64308 | 0.10724 | 0.15681 | 0.00964 | 1095 | 22 | 939 | 53 | 15 |
| 62 | 138808 | 87 | 0.07471 | 0.00117 | 1.64501 | 0.10359 | 0.15969 | 0.00974 | 1061 | 16 | 955 | 54 | 11 |
| 63 | 35311 | 95 | 0.08393 | 0.00203 | 1.84968 | 0.11942 | 0.15984 | 0.00957 | 1291 | 24 | 956 | 53 | 28 |

Appendix 1

*(continued)*

| Grain # | $^{206}Pb$ (cps) | $^{204}Pb$ (cps) | $\frac{^{207}Pb}{^{206}Pb}$ | 2σ | $\frac{^{207}Pb}{^{235}U}$ | 2σ | $\frac{^{206}Pb}{^{238}U}$ | 2σ | age (Ma) $\frac{^{207}Pb}{^{206}Pb}$ | 2σ | age (Ma) $\frac{^{206}Pb}{^{238}U}$ | 2σ | disc. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample 10BUNKER01 - Bunker Hill sequence volcanic member | | | | | | | | | | | | | |
| 64 | 141389 | 98 | 0.10148 | 0.00153 | 3.68955 | 0.23223 | 0.26368 | 0.01611 | 1651 | 14 | 1509 | 82 | 10 |
| 65 | 42198 | 90 | 0.07991 | 0.00155 | 1.64040 | 0.11030 | 0.14889 | 0.00959 | 1195 | 19 | 895 | 54 | 27 |
| 67 | 23267 | 109 | 0.14732 | 0.00294 | 7.35248 | 0.53305 | 0.36196 | 0.02523 | 2315 | 17 | 1991 | 118 | 16 |
| 68 | 66870 | 140 | 0.07869 | 0.00143 | 1.75535 | 0.10939 | 0.16178 | 0.00965 | 1164 | 18 | 967 | 53 | 18 |
| 69 | 324907 | 132 | 0.07519 | 0.00110 | 1.75054 | 0.10926 | 0.16886 | 0.01025 | 1074 | 15 | 1006 | 56 | 7 |
| 72 | 36471 | 44 | 0.08383 | 0.00213 | 1.79236 | 0.13171 | 0.15507 | 0.01069 | 1289 | 25 | 929 | 59 | 30 |
| 74 | 14676 | 53 | 0.12838 | 0.00493 | 4.93332 | 0.35721 | 0.27871 | 0.01711 | 2076 | 34 | 1585 | 86 | 27 |
| 78 | 38988 | 40 | 0.08477 | 0.00176 | 1.88215 | 0.13582 | 0.16104 | 0.01113 | 1310 | 20 | 963 | 62 | 29 |
| 79 | 86252 | 44 | 0.07614 | 0.00137 | 1.59125 | 0.10399 | 0.15157 | 0.00952 | 1099 | 18 | 910 | 53 | 18 |
| 80 | 143416 | 66 | 0.18894 | 0.00273 | 12.30662 | 0.93979 | 0.47241 | 0.03542 | 2733 | 12 | 2494 | 153 | 11 |
| 82 | 114198 | 68 | 0.07646 | 0.00133 | 1.65052 | 0.13130 | 0.15655 | 0.01215 | 1107 | 17 | 938 | 67 | 16 |
| 83 | 80508 | 85 | 0.19694 | 0.00296 | 12.46495 | 0.87478 | 0.45905 | 0.03147 | 2801 | 12 | 2435 | 138 | 16 |
| 85 | 194771 | 128 | 0.07515 | 0.00113 | 1.64858 | 0.12863 | 0.15910 | 0.01218 | 1073 | 15 | 952 | 67 | 12 |
| 87 | 126828 | 53 | 0.10161 | 0.00151 | 3.70568 | 0.24222 | 0.26451 | 0.01683 | 1654 | 14 | 1513 | 85 | 10 |
| 88 | 59997 | 54 | 0.07943 | 0.00150 | 1.72088 | 0.10538 | 0.15712 | 0.00915 | 1183 | 19 | 941 | 51 | 22 |
| 90 | 107390 | 50 | 0.07626 | 0.00136 | 1.59238 | 0.10645 | 0.15145 | 0.00976 | 1102 | 18 | 909 | 54 | 19 |
| 92 | 243046 | 69 | 0.18264 | 0.00263 | 11.85198 | 0.81979 | 0.47064 | 0.03184 | 2677 | 12 | 2486 | 138 | 9 |
| 93 | 10419 | 63 | 0.10736 | 0.00337 | 2.40617 | 0.16620 | 0.16255 | 0.01000 | 1755 | 29 | 971 | 55 | 48 |
| 95 | 617652 | 51 | 0.11195 | 0.00161 | 4.62471 | 0.32772 | 0.29960 | 0.02079 | 1831 | 13 | 1689 | 102 | 9 |
| 97 | 26700 | 41 | 0.14286 | 0.00265 | 7.16060 | 0.47108 | 0.36353 | 0.02294 | 2262 | 16 | 1999 | 108 | 14 |
| 101 | 148658 | 28 | 0.07647 | 0.00115 | 1.67101 | 0.10408 | 0.15848 | 0.00958 | 1107 | 15 | 948 | 53 | 15 |
| 103 | 197894 | 32 | 0.07368 | 0.00113 | 1.63734 | 0.11843 | 0.16118 | 0.01139 | 1033 | 15 | 963 | 63 | 7 |
| 106 | 139917 | 10 | 0.10074 | 0.00131 | 3.54382 | 0.22387 | 0.25514 | 0.01577 | 1638 | 12 | 1465 | 81 | 12 |
| 107 | 583945 | 12 | 0.11154 | 0.00142 | 4.85861 | 0.36329 | 0.31591 | 0.02328 | 1825 | 12 | 1770 | 113 | 3 |
| 108 | 11826 | 13 | 0.09154 | 0.00308 | 2.33558 | 0.14724 | 0.18504 | 0.00986 | 1458 | 32 | 1094 | 53 | 27 |
| 109 | 37562 | 8 | 0.07877 | 0.00149 | 1.62015 | 0.12444 | 0.14918 | 0.01111 | 1166 | 19 | 896 | 62 | 25 |
| 110 | 10378 | 7 | 0.09487 | 0.00329 | 2.51522 | 0.16321 | 0.19228 | 0.01055 | 1526 | 33 | 1134 | 57 | 28 |
| 111 | 21208 | 6 | 0.08180 | 0.00218 | 1.69359 | 0.11497 | 0.15016 | 0.00937 | 1241 | 26 | 902 | 52 | 29 |
| 112 | 203062 | 5 | 0.07440 | 0.00097 | 1.71282 | 0.08689 | 0.16697 | 0.00818 | 1052 | 13 | 995 | 45 | 6 |
| 113 | 322931 | 4 | 0.18529 | 0.00236 | 12.91283 | 0.70512 | 0.50545 | 0.02684 | 2701 | 11 | 2637 | 114 | 3 |
| 114 | 82128 | 4 | 0.10088 | 0.00137 | 3.63171 | 0.17982 | 0.26109 | 0.01243 | 1640 | 13 | 1495 | 63 | 10 |
| 115 | 9717 | 7 | 0.09577 | 0.00352 | 2.51753 | 0.17828 | 0.19066 | 0.01154 | 1543 | 35 | 1125 | 62 | 30 |
| 116 | 16924 | 48 | 0.07314 | 0.00158 | 1.83281 | 0.09700 | 0.18174 | 0.00878 | 1018 | 22 | 1076 | 48 | -6 |
| 117 | 113114 | 52 | 0.07094 | 0.00100 | 1.47517 | 0.07629 | 0.15082 | 0.00750 | 956 | 14 | 906 | 42 | 6 |
| 118 | 13993 | 45 | 0.09620 | 0.00209 | 3.76412 | 0.21633 | 0.28379 | 0.01510 | 1552 | 20 | 1610 | 75 | -4 |
| 119 | 436312 | 48 | 0.16767 | 0.00213 | 9.73390 | 0.56446 | 0.42104 | 0.02382 | 2535 | 11 | 2265 | 107 | 13 |
| 120 | 48193 | 38 | 0.07319 | 0.00111 | 1.73203 | 0.10583 | 0.17164 | 0.01016 | 1019 | 15 | 1021 | 56 | 0 |
| 121 | 643564 | 42 | 0.16475 | 0.00215 | 8.10778 | 0.59116 | 0.35692 | 0.02560 | 2505 | 11 | 1968 | 120 | 25 |
| 122 | 104745 | 16 | 0.20363 | 0.00262 | 14.10875 | 0.85271 | 0.50252 | 0.02968 | 2855 | 10 | 2625 | 126 | 10 |
| 124 | 152724 | 23 | 0.09911 | 0.00132 | 3.57305 | 0.20905 | 0.26146 | 0.01489 | 1608 | 12 | 1497 | 76 | 8 |
| 125 | 24196 | 23 | 0.07198 | 0.00118 | 1.70258 | 0.09846 | 0.17155 | 0.00952 | 985 | 17 | 1021 | 52 | -4 |
| 126 | 52872 | 10 | 0.08317 | 0.00121 | 2.34707 | 0.16271 | 0.20468 | 0.01387 | 1273 | 14 | 1200 | 74 | 6 |
| 127 | 28286 | 29 | 0.06864 | 0.00131 | 1.47704 | 0.08212 | 0.15606 | 0.00815 | 888 | 20 | 935 | 45 | -6 |
| 128 | 512182 | 12 | 0.11228 | 0.00142 | 4.98176 | 0.34522 | 0.32179 | 0.02192 | 1837 | 11 | 1798 | 106 | 2 |
| 129 | 48875 | 16 | 0.07374 | 0.00105 | 1.69448 | 0.08804 | 0.16667 | 0.00833 | 1034 | 14 | 994 | 46 | 4 |
| 130 | 92647 | 5 | 0.09235 | 0.00127 | 3.02502 | 0.15716 | 0.23757 | 0.01190 | 1475 | 13 | 1374 | 62 | 8 |
| Sample 09SV01 - Saint-Victor Formation | | | | | | | | | | | | | |
| 1 | 59193 | 35 | 0.08655 | 0.00169 | 2.54752 | 0.15751 | 0.21347 | 0.01253 | 1351 | 38 | 1247 | 66 | 8 |
| 2 | 23090 | 29 | 0.06876 | 0.00184 | 1.63054 | 0.13242 | 0.17199 | 0.01318 | 892 | 55 | 1023 | 72 | -16 |
| 3 | 29344 | 36 | 0.07356 | 0.00355 | 1.71492 | 0.14935 | 0.16909 | 0.01225 | 1029 | 98 | 1007 | 67 | 2 |
| 4 | 34357 | 14 | 0.09675 | 0.00122 | 3.81820 | 0.22835 | 0.28624 | 0.01673 | 1562 | 24 | 1623 | 83 | -4 |
| 5 | 165848 | 17 | 0.07493 | 0.00063 | 1.79540 | 0.11579 | 0.17378 | 0.01111 | 1067 | 17 | 1033 | 61 | 3 |
| 6 | 241400 | 25 | 0.18652 | 0.00132 | 13.11043 | 0.93625 | 0.50979 | 0.03623 | 2712 | 12 | 2656 | 153 | 3 |
| 7 | 45402 | 13 | 0.07308 | 0.00124 | 1.68656 | 0.10498 | 0.16737 | 0.01002 | 1016 | 34 | 998 | 55 | 2 |
| 8 | 17785 | 8 | 0.06859 | 0.00168 | 1.70016 | 0.10624 | 0.17977 | 0.01034 | 886 | 51 | 1066 | 56 | -22 |
| 9 | 44198 | 14 | 0.08329 | 0.00138 | 2.41414 | 0.19805 | 0.21023 | 0.01689 | 1276 | 32 | 1230 | 89 | 4 |
| 10 | 353013 | 12 | 0.18923 | 0.00163 | 12.56189 | 0.82870 | 0.48146 | 0.03149 | 2736 | 14 | 2534 | 136 | 9 |
| 11 | 134151 | 21 | 0.28094 | 0.00295 | 24.64147 | 1.40962 | 0.63615 | 0.03577 | 3368 | 16 | 3174 | 139 | 7 |
| 12 | 15348 | 7 | 0.06720 | 0.00181 | 1.67629 | 0.12253 | 0.18091 | 0.01230 | 844 | 56 | 1072 | 67 | -29 |
| 14 | 40651 | 13 | 0.09761 | 0.00121 | 3.55784 | 0.19896 | 0.26435 | 0.01441 | 1579 | 23 | 1512 | 73 | 5 |
| 15 | 155586 | 15 | 0.07256 | 0.00066 | 1.62668 | 0.09785 | 0.16258 | 0.00967 | 1002 | 18 | 971 | 53 | 3 |
| 16 | 17241 | 21 | 0.07827 | 0.00200 | 2.64750 | 0.16189 | 0.24532 | 0.01363 | 1154 | 51 | 1414 | 70 | -25 |
| 17 | 24028 | 14 | 0.07380 | 0.00159 | 1.89077 | 0.13149 | 0.18581 | 0.01229 | 1036 | 43 | 1099 | 66 | -7 |
| 18 | 17405 | 22 | 0.07345 | 0.00322 | 1.80389 | 0.15223 | 0.17811 | 0.01284 | 1027 | 89 | 1057 | 70 | -3 |
| 19 | 9167 | 13 | 0.07424 | 0.00558 | 1.86724 | 0.20109 | 0.18241 | 0.01408 | 1048 | 151 | 1080 | 76 | -3 |
| 20 | 1182326 | 26 | 0.17659 | 0.00123 | 11.37709 | 0.81571 | 0.46726 | 0.03334 | 2621 | 12 | 2472 | 145 | 7 |
| 21 | 22022 | 49 | 0.07013 | 0.00292 | 1.53693 | 0.10729 | 0.15895 | 0.00890 | 932 | 86 | 951 | 49 | -2 |
| 22 | 54064 | 46 | 0.08579 | 0.00125 | 2.59932 | 0.14363 | 0.21976 | 0.01171 | 1333 | 28 | 1281 | 62 | 4 |
| 23 | 150238 | 43 | 0.20052 | 0.00148 | 14.99191 | 0.86809 | 0.54225 | 0.03114 | 2830 | 12 | 2793 | 129 | 2 |
| 24 | 976571 | 84 | 0.11332 | 0.00076 | 5.18280 | 0.30655 | 0.33170 | 0.01949 | 1853 | 12 | 1847 | 94 | 0 |
| 25 | 111980 | 63 | 0.07770 | 0.00068 | 2.04708 | 0.11110 | 0.19109 | 0.01023 | 1139 | 18 | 1127 | 55 | 1 |
| 26 | 27221 | 59 | 0.08409 | 0.00160 | 2.55731 | 0.14737 | 0.22056 | 0.01200 | 1295 | 37 | 1285 | 63 | 1 |
| 27 | 55836 | 65 | 0.07915 | 0.00101 | 2.09680 | 0.12612 | 0.19214 | 0.01129 | 1176 | 25 | 1133 | 61 | 4 |
| 28 | 261129 | 61 | 0.08827 | 0.00070 | 2.83093 | 0.15961 | 0.23260 | 0.01298 | 1388 | 15 | 1348 | 68 | 3 |
| 29 | 53808 | 80 | 0.07408 | 0.00117 | 1.74566 | 0.11272 | 0.17091 | 0.01070 | 1044 | 32 | 1017 | 59 | 3 |

Appendix 1

*(continued)*

| Grain # | $^{206}Pb$ (cps) | $^{204}Pb$ (cps) | $\frac{^{207}Pb}{^{206}Pb}$ | 2σ | $\frac{^{207}Pb}{^{235}U}$ | 2σ | $\frac{^{206}Pb}{^{238}U}$ | 2σ | age (Ma) $\frac{^{207}Pb}{^{206}Pb}$ | 2σ | age (Ma) $\frac{^{206}Pb}{^{238}U}$ | 2σ | disc. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample 09SV01 - Saint-Victor Formation | | | | | | | | | | | | | |
| 30 | 158044 | 67 | 0.10776 | 0.00127 | 4.30896 | 0.25146 | 0.29002 | 0.01658 | 1762 | 22 | 1642 | 82 | 8 |
| 31 | 45484 | 76 | 0.07474 | 0.00105 | 1.76355 | 0.10498 | 0.17113 | 0.00990 | 1062 | 28 | 1018 | 54 | 4 |
| 33 | 30889 | 74 | 0.07371 | 0.00134 | 1.73567 | 0.10365 | 0.17078 | 0.00971 | 1034 | 37 | 1016 | 53 | 2 |
| 34 | 102827 | 82 | 0.07477 | 0.00071 | 1.80501 | 0.09941 | 0.17509 | 0.00950 | 1062 | 19 | 1040 | 52 | 2 |
| 35 | 34151 | 71 | 0.07653 | 0.00106 | 2.01717 | 0.11654 | 0.19117 | 0.01072 | 1109 | 28 | 1128 | 58 | -2 |
| 36 | 57536 | 85 | 0.07438 | 0.00095 | 1.75402 | 0.09911 | 0.17103 | 0.00941 | 1052 | 26 | 1018 | 52 | 4 |
| 37 | 31783 | 60 | 0.07257 | 0.00092 | 1.66371 | 0.10287 | 0.16628 | 0.01006 | 1002 | 26 | 992 | 55 | 1 |
| 38 | 74422 | 65 | 0.10361 | 0.00105 | 3.97868 | 0.23398 | 0.27851 | 0.01613 | 1690 | 19 | 1584 | 81 | 7 |
| 39 | 67351 | 76 | 0.08252 | 0.00100 | 2.34338 | 0.15271 | 0.20597 | 0.01319 | 1258 | 24 | 1207 | 70 | 4 |
| 40 | 52924 | 71 | 0.09046 | 0.00103 | 2.95989 | 0.19238 | 0.23731 | 0.01519 | 1435 | 22 | 1373 | 79 | 5 |
| 41 | 115703 | 77 | 0.11320 | 0.00097 | 4.98715 | 0.30609 | 0.31952 | 0.01942 | 1851 | 15 | 1787 | 94 | 4 |
| 42 | 11835 | 64 | 0.07712 | 0.00323 | 2.04391 | 0.14151 | 0.19223 | 0.01059 | 1124 | 84 | 1133 | 57 | -1 |
| 43 | 121166 | 80 | 0.07533 | 0.00069 | 1.79255 | 0.10342 | 0.17259 | 0.00983 | 1077 | 18 | 1026 | 54 | 5 |
| 44 | 651023 | 75 | 0.11343 | 0.00077 | 5.02819 | 0.35433 | 0.32149 | 0.02255 | 1855 | 12 | 1797 | 109 | 4 |
| 45 | 165881 | 83 | 0.11453 | 0.00082 | 5.11032 | 0.29683 | 0.32361 | 0.01865 | 1873 | 13 | 1807 | 90 | 4 |
| 46 | 15338 | 101 | 0.08914 | 0.00378 | 2.40210 | 0.17807 | 0.19545 | 0.01188 | 1407 | 81 | 1151 | 64 | 20 |
| 47 | 191919 | 120 | 0.11584 | 0.00114 | 5.10203 | 0.27571 | 0.31943 | 0.01697 | 1893 | 18 | 1787 | 82 | 6 |
| 48 | 82841 | 93 | 0.08504 | 0.00084 | 2.43923 | 0.14080 | 0.20804 | 0.01183 | 1316 | 19 | 1218 | 63 | 8 |
| 49 | 75164 | 127 | 0.09427 | 0.00108 | 3.24703 | 0.21803 | 0.24981 | 0.01653 | 1514 | 22 | 1438 | 85 | 6 |
| 50 | 213192 | 105 | 0.19233 | 0.00138 | 13.82129 | 0.78787 | 0.52119 | 0.02947 | 2762 | 12 | 2704 | 124 | 3 |
| 51 | 62352 | 107 | 0.08939 | 0.00077 | 2.92883 | 0.16887 | 0.23763 | 0.01355 | 1413 | 17 | 1374 | 70 | 3 |
| 52 | 24604 | 106 | 0.07202 | 0.00109 | 1.57598 | 0.09865 | 0.15871 | 0.00964 | 987 | 31 | 950 | 53 | 4 |
| 53 | 208490 | 104 | 0.18739 | 0.00136 | 13.15129 | 0.73260 | 0.50901 | 0.02811 | 2719 | 12 | 2652 | 119 | 3 |
| 54 | 11850 | 102 | 0.07442 | 0.00151 | 1.85363 | 0.11465 | 0.18064 | 0.01055 | 1053 | 41 | 1070 | 57 | -2 |
| 55 | 100080 | 122 | 0.19187 | 0.00141 | 13.15731 | 0.75594 | 0.49734 | 0.02834 | 2758 | 12 | 2602 | 121 | 7 |
| 56 | 75519 | 122 | 0.08540 | 0.00076 | 2.60687 | 0.15972 | 0.22139 | 0.01342 | 1325 | 17 | 1289 | 70 | 3 |
| 57 | 19579 | 116 | 0.07429 | 0.00273 | 1.88173 | 0.12866 | 0.18371 | 0.01059 | 1049 | 74 | 1087 | 57 | -4 |
| 58 | 24069 | 110 | 0.07152 | 0.00151 | 1.64210 | 0.10929 | 0.16652 | 0.01051 | 972 | 43 | 993 | 58 | -2 |
| 59 | 27830 | 117 | 0.07610 | 0.00126 | 1.87503 | 0.11254 | 0.17871 | 0.01031 | 1098 | 33 | 1060 | 56 | 4 |
| 60 | 7971 | 121 | 0.07717 | 0.00239 | 2.05199 | 0.12830 | 0.19284 | 0.01048 | 1126 | 62 | 1137 | 56 | -1 |
| 61 | 425912 | 81 | 0.19215 | 0.00130 | 13.50325 | 0.77048 | 0.50967 | 0.02888 | 2761 | 11 | 2655 | 122 | 5 |
| 62 | 99219 | 62 | 0.18899 | 0.00135 | 12.87859 | 0.73601 | 0.49424 | 0.02803 | 2733 | 12 | 2589 | 120 | 6 |
| 63 | 81270 | 61 | 0.09993 | 0.00085 | 3.81269 | 0.22170 | 0.27672 | 0.01592 | 1623 | 16 | 1575 | 80 | 3 |
| 64 | 61409 | 80 | 0.07474 | 0.00066 | 1.76426 | 0.10496 | 0.17121 | 0.01007 | 1061 | 18 | 1019 | 55 | 4 |
| 65 | 42734 | 74 | 0.09199 | 0.00093 | 3.04614 | 0.17411 | 0.24017 | 0.01351 | 1467 | 19 | 1388 | 70 | 6 |
| 66 | 906221 | 75 | 0.18107 | 0.00121 | 12.60496 | 0.72763 | 0.50489 | 0.02895 | 2663 | 11 | 2635 | 123 | 1 |
| 67 | 190036 | 74 | 0.07556 | 0.00056 | 1.84302 | 0.10124 | 0.17691 | 0.00963 | 1083 | 15 | 1050 | 53 | 3 |
| 68 | 25760 | 41 | 0.06833 | 0.00113 | 1.51176 | 0.08907 | 0.16046 | 0.00907 | 879 | 34 | 959 | 50 | -10 |
| 69 | 170425 | 213 | 0.07908 | 0.00074 | 2.07512 | 0.11867 | 0.19031 | 0.01074 | 1174 | 19 | 1123 | 58 | 5 |
| 70 | 92425 | 69 | 0.07611 | 0.00069 | 1.87269 | 0.10981 | 0.17845 | 0.01034 | 1098 | 18 | 1058 | 56 | 4 |
| 71 | 54790 | 43 | 0.08455 | 0.00088 | 2.59050 | 0.15125 | 0.22221 | 0.01277 | 1305 | 20 | 1294 | 67 | 1 |
| 72 | 368079 | 42 | 0.07272 | 0.00056 | 1.61697 | 0.08797 | 0.16127 | 0.00869 | 1006 | 16 | 964 | 48 | 5 |
| 73 | 81589 | 34 | 0.09000 | 0.00078 | 3.00738 | 0.17228 | 0.24236 | 0.01373 | 1425 | 16 | 1399 | 71 | 2 |
| 74 | 26279 | 26 | 0.07102 | 0.00116 | 1.63901 | 0.09611 | 0.16737 | 0.00943 | 958 | 33 | 998 | 52 | -4 |
| 78 | 107939 | 47 | 0.08185 | 0.00072 | 2.25508 | 0.14364 | 0.19982 | 0.01260 | 1242 | 17 | 1174 | 67 | 6 |
| 76 | 35086 | 40 | 0.07187 | 0.00089 | 1.52286 | 0.09885 | 0.15368 | 0.00979 | 982 | 25 | 922 | 54 | 7 |
| 77 | 19314 | 44 | 0.07025 | 0.00128 | 1.60996 | 0.09670 | 0.16621 | 0.00951 | 936 | 37 | 991 | 52 | -6 |
| 78 | 55243 | 43 | 0.08816 | 0.00088 | 2.66896 | 0.14954 | 0.21957 | 0.01210 | 1386 | 19 | 1280 | 64 | 8 |
| 79 | 51983 | 34 | 0.08465 | 0.00085 | 2.39114 | 0.12983 | 0.20486 | 0.01093 | 1308 | 19 | 1201 | 58 | 9 |
| 80 | 49602 | 23 | 0.07802 | 0.00076 | 1.95129 | 0.10872 | 0.18140 | 0.00995 | 1147 | 19 | 1075 | 54 | 7 |
| 81 | 349459 | 25 | 0.11373 | 0.00078 | 4.81231 | 0.27042 | 0.30690 | 0.01712 | 1860 | 12 | 1725 | 84 | 8 |
| 82 | 342365 | 26 | 0.11329 | 0.00079 | 4.73762 | 0.27126 | 0.30330 | 0.01724 | 1853 | 13 | 1708 | 85 | 9 |
| 83 | 77850 | 46 | 0.07129 | 0.00068 | 1.48662 | 0.08317 | 0.15124 | 0.00834 | 966 | 19 | 908 | 47 | 6 |
| 84 | 248422 | 40 | 0.07352 | 0.00054 | 1.62410 | 0.09826 | 0.16022 | 0.00962 | 1028 | 15 | 958 | 53 | 7 |
| 85 | 20685 | 27 | 0.12833 | 0.00135 | 6.53766 | 0.43117 | 0.36948 | 0.02406 | 2075 | 18 | 2027 | 112 | 3 |
| Sample 09SV02 - Saint-Victor Formation | | | | | | | | | | | | | |
| 1 | 24720 | 47 | 0.05221 | 0.00119 | 0.42930 | 0.01891 | 0.05964 | 0.00225 | 294 | 52 | 373 | 14 | -28 |
| 2 | 41568 | 52 | 0.09922 | 0.00171 | 3.13680 | 0.12178 | 0.22929 | 0.00798 | 1610 | 32 | 1331 | 42 | 19 |
| 3 | 318474 | 58 | 0.07258 | 0.00100 | 1.51230 | 0.05523 | 0.15113 | 0.00511 | 1002 | 28 | 907 | 29 | 10 |
| 4 | 10248 | 56 | 0.06755 | 0.00214 | 1.39394 | 0.06583 | 0.14966 | 0.00524 | 855 | 66 | 899 | 29 | -6 |
| 5 | 41297 | 74 | 0.05507 | 0.00120 | 0.51728 | 0.02173 | 0.06812 | 0.00244 | 415 | 49 | 425 | 15 | -2 |
| 6 | 52960 | 78 | 0.07214 | 0.00188 | 1.30342 | 0.08667 | 0.13105 | 0.00802 | 990 | 53 | 794 | 46 | 21 |
| 7 | 69341 | 58 | 0.05451 | 0.00058 | 0.50959 | 0.02133 | 0.06780 | 0.00275 | 392 | 24 | 423 | 17 | -8 |
| 9 | 107422 | 88 | 0.11610 | 0.00178 | 4.24839 | 0.21181 | 0.26540 | 0.01259 | 1897 | 28 | 1517 | 64 | 22 |
| 10 | 42310 | 69 | 0.06780 | 0.00123 | 1.00002 | 0.05511 | 0.10697 | 0.00557 | 862 | 38 | 655 | 32 | 25 |
| 11 | 221688 | 87 | 0.07383 | 0.00111 | 1.35366 | 0.24230 | 0.13298 | 0.02372 | 1037 | 30 | 805 | 134 | 24 |
| 12 | 12300 | 64 | 0.08232 | 0.00285 | 2.31363 | 0.39519 | 0.20385 | 0.03410 | 1253 | 68 | 1196 | 180 | 5 |
| 13 | 67017 | 46 | 0.05382 | 0.00073 | 0.51728 | 0.01998 | 0.06971 | 0.00252 | 363 | 31 | 434 | 15 | -20 |
| 14 | 36608 | 84 | 0.10115 | 0.00207 | 3.37715 | 0.57800 | 0.24214 | 0.04115 | 1645 | 38 | 1398 | 210 | 17 |
| 15 | 67317 | 29 | 0.05402 | 0.00071 | 0.51683 | 0.01870 | 0.06939 | 0.00234 | 372 | 30 | 432 | 14 | -17 |
| 16 | 59565 | 67 | 0.09892 | 0.00144 | 3.26468 | 0.55500 | 0.23937 | 0.04054 | 1604 | 27 | 1383 | 208 | 15 |
| 17 | 30028 | 56 | 0.07065 | 0.00145 | 1.43676 | 0.24133 | 0.14750 | 0.02459 | 947 | 42 | 887 | 137 | 7 |
| 18 | 38246 | 42 | 0.05423 | 0.00130 | 0.51564 | 0.02262 | 0.06897 | 0.00254 | 381 | 54 | 430 | 15 | -13 |
| 19 | 58649 | 48 | 0.05400 | 0.00074 | 0.51593 | 0.01992 | 0.06929 | 0.00250 | 371 | 31 | 432 | 15 | -17 |
| 19 | 58649 | 48 | 0.05400 | 0.00074 | 0.51593 | 0.01992 | 0.06929 | 0.00250 | 371 | 31 | 432 | 15 | -17 |

Appendix 1

*(continued)*

| | | | | | | | age (Ma) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Grain # | $^{206}Pb$ (cps) | $^{204}Pb$ (cps) | $\frac{^{207}Pb}{^{206}Pb}$ | 2σ | $\frac{^{207}Pb}{^{235}U}$ | 2σ | $\frac{^{206}Pb}{^{238}U}$ | 2σ | $\frac{^{207}Pb}{^{206}Pb}$ | 2σ | $\frac{^{206}Pb}{^{238}U}$ | 2σ | disc. |
| Sample 09SV02 - Saint-Victor Formation | | | | | | | | | | | | | |
| 20 | 81858 | 69 | 0.11342 | 0.00172 | 4.11349 | 0.69460 | 0.26303 | 0.04424 | 1855 | 27 | 1505 | 222 | 21 |
| 21 | 68623 | 68 | 0.05694 | 0.00148 | 0.54980 | 0.02503 | 0.07003 | 0.00262 | 489 | 57 | 436 | 16 | 11 |
| 22 | 37807 | 73 | 0.08229 | 0.00127 | 2.32095 | 0.17934 | 0.20456 | 0.01549 | 1252 | 30 | 1200 | 82 | 5 |
| 24 | 32511 | 79 | 0.05446 | 0.00096 | 0.48997 | 0.03863 | 0.06525 | 0.00501 | 390 | 40 | 407 | 30 | -5 |
| 25 | 13643 | 63 | 0.06731 | 0.00211 | 1.64933 | 0.12981 | 0.17772 | 0.01283 | 847 | 65 | 1055 | 70 | -27 |
| 27 | 26973 | 85 | 0.05629 | 0.00127 | 0.50874 | 0.03971 | 0.06555 | 0.00490 | 464 | 50 | 409 | 30 | 12 |
| 28 | 131509 | 74 | 0.07223 | 0.00106 | 1.53807 | 0.11564 | 0.15445 | 0.01139 | 992 | 30 | 926 | 63 | 7 |
| 29 | 58159 | 56 | 0.05624 | 0.00100 | 0.53109 | 0.02056 | 0.06849 | 0.00235 | 462 | 40 | 427 | 14 | 8 |
| 30 | 25735 | 77 | 0.05345 | 0.00158 | 0.50125 | 0.04128 | 0.06802 | 0.00523 | 348 | 67 | 424 | 31 | -23 |
| 31 | 33548 | 95 | 0.07078 | 0.00145 | 1.66908 | 0.25471 | 0.17103 | 0.02586 | 951 | 42 | 1018 | 141 | -8 |
| 32 | 94906 | 78 | 0.07226 | 0.00104 | 1.70301 | 0.25988 | 0.17094 | 0.02597 | 993 | 29 | 1017 | 141 | -3 |
| 33 | 74276 | 38 | 0.05433 | 0.00075 | 0.50491 | 0.01887 | 0.06741 | 0.00234 | 385 | 31 | 421 | 14 | -10 |
| 34 | 66980 | 88 | 0.07381 | 0.00126 | 1.71467 | 0.26082 | 0.16848 | 0.02546 | 1036 | 35 | 1004 | 139 | 3 |
| 35 | 28980 | 112 | 0.07410 | 0.00180 | 1.61373 | 0.24978 | 0.15796 | 0.02415 | 1044 | 49 | 945 | 133 | 10 |
| 36 | 54000 | 37 | 0.05351 | 0.00114 | 0.49636 | 0.01986 | 0.06727 | 0.00227 | 351 | 48 | 420 | 14 | -20 |
| 37 | 37931 | 98 | 0.07224 | 0.00125 | 1.75355 | 0.26411 | 0.17605 | 0.02634 | 993 | 35 | 1045 | 143 | -6 |
| 39 | 78701 | 80 | 0.07261 | 0.00113 | 1.69946 | 0.25692 | 0.16976 | 0.02553 | 1003 | 32 | 1011 | 139 | -1 |
| 41 | 65246 | 48 | 0.08384 | 0.00142 | 2.45143 | 0.25701 | 0.21207 | 0.02194 | 1289 | 33 | 1240 | 116 | 4 |
| 42 | 45262 | 53 | 0.07201 | 0.00130 | 1.66831 | 0.17314 | 0.16802 | 0.01717 | 986 | 37 | 1001 | 94 | -2 |
| 43 | 36835 | 47 | 0.06805 | 0.00114 | 1.42344 | 0.14684 | 0.15172 | 0.01544 | 870 | 35 | 911 | 86 | -5 |
| 44 | 64539 | 51 | 0.07184 | 0.00116 | 1.58044 | 0.16382 | 0.15955 | 0.01633 | 981 | 33 | 954 | 90 | 3 |
| 45 | 138238 | 63 | 0.05554 | 0.00060 | 0.50643 | 0.02082 | 0.06613 | 0.00262 | 434 | 24 | 413 | 16 | 5 |
| 46 | 55111 | 51 | 0.09101 | 0.00137 | 2.94837 | 0.31024 | 0.23495 | 0.02447 | 1447 | 29 | 1360 | 126 | 7 |
| 47 | 127955 | 71 | 0.07261 | 0.00112 | 1.60381 | 0.16561 | 0.16019 | 0.01636 | 1003 | 31 | 958 | 90 | 5 |
| 48 | 55584 | 72 | 0.05604 | 0.00131 | 0.53741 | 0.02239 | 0.06955 | 0.00240 | 454 | 52 | 433 | 14 | 5 |
| 49 | 85751 | 75 | 0.05460 | 0.00070 | 0.51715 | 0.01901 | 0.06870 | 0.00237 | 396 | 29 | 428 | 14 | -9 |
| 50 | 44062 | 50 | 0.05316 | 0.00131 | 0.48218 | 0.05177 | 0.06578 | 0.00687 | 336 | 56 | 411 | 41 | -23 |
| 51 | 37581 | 70 | 0.08105 | 0.00450 | 1.92124 | 0.21440 | 0.17191 | 0.01664 | 1223 | 109 | 1023 | 91 | 18 |
| 52 | 45513 | 47 | 0.05335 | 0.00085 | 0.47422 | 0.04571 | 0.06447 | 0.00613 | 344 | 36 | 403 | 37 | -18 |
| 53 | 40314 | 60 | 0.05469 | 0.00141 | 0.50114 | 0.02241 | 0.06646 | 0.00242 | 399 | 58 | 415 | 15 | -4 |
| 54 | 15145 | 43 | 0.05390 | 0.00449 | 0.51559 | 0.06416 | 0.06938 | 0.00641 | 367 | 188 | 432 | 39 | -19 |
| 55 | 22297 | 68 | 0.05441 | 0.00337 | 0.48625 | 0.03570 | 0.06482 | 0.00255 | 388 | 139 | 405 | 15 | -5 |
| 56 | 66833 | 95 | 0.05569 | 0.00198 | 0.51697 | 0.02595 | 0.06733 | 0.00238 | 440 | 79 | 420 | 14 | 5 |
| 58 | 17542 | 64 | 0.07791 | 0.00515 | 1.95753 | 0.22157 | 0.18222 | 0.01675 | 1145 | 131 | 1079 | 91 | 6 |
| 59 | 41116 | 47 | 0.07324 | 0.00160 | 1.66857 | 0.15628 | 0.16523 | 0.01505 | 1021 | 44 | 986 | 83 | 4 |
| 60 | 51574 | 38 | 0.07410 | 0.00132 | 1.65307 | 0.15398 | 0.16179 | 0.01479 | 1044 | 36 | 967 | 82 | 8 |
| 61 | 14574 | 46 | 0.06771 | 0.00287 | 1.71992 | 0.08676 | 0.18424 | 0.00503 | 860 | 88 | 1090 | 27 | -29 |
| 62 | 32389 | 38 | 0.05366 | 0.00123 | 0.49618 | 0.01676 | 0.06706 | 0.00166 | 357 | 52 | 418 | 10 | -18 |
| 64 | 22469 | 28 | 0.06849 | 0.00135 | 1.54099 | 0.04819 | 0.16318 | 0.00395 | 883 | 41 | 974 | 22 | -11 |
| 65 | 25123 | 40 | 0.07129 | 0.00178 | 1.93033 | 0.06365 | 0.19638 | 0.00424 | 966 | 51 | 1156 | 23 | -22 |
| 67 | 34778 | 198 | 0.05757 | 0.00332 | 0.52521 | 0.03840 | 0.06617 | 0.00297 | 513 | 127 | 413 | 18 | 20 |
| 68 | 37582 | 46 | 0.07438 | 0.00202 | 1.72468 | 0.05927 | 0.16817 | 0.00354 | 1052 | 55 | 1002 | 20 | 5 |
| 69 | 88669 | 37 | 0.05572 | 0.00105 | 0.59390 | 0.01889 | 0.07731 | 0.00198 | 441 | 42 | 480 | 12 | -9 |
| 70 | 31319 | 35 | 0.06778 | 0.00158 | 1.65567 | 0.05081 | 0.17716 | 0.00354 | 862 | 48 | 1051 | 19 | -24 |
| 71 | 65931 | 47 | 0.08206 | 0.00136 | 2.31556 | 0.14984 | 0.20465 | 0.01280 | 1247 | 32 | 1200 | 68 | 4 |
| 72 | 66805 | 60 | 0.05512 | 0.00096 | 0.48865 | 0.02618 | 0.06430 | 0.00326 | 417 | 39 | 402 | 20 | 4 |
| 73 | 46113 | 59 | 0.05274 | 0.00106 | 0.45988 | 0.02202 | 0.06324 | 0.00275 | 318 | 46 | 395 | 17 | -25 |
| 74 | 104009 | 97 | 0.05638 | 0.00120 | 0.52602 | 0.03015 | 0.06767 | 0.00360 | 467 | 47 | 422 | 22 | 10 |
| 75 | 32451 | 61 | 0.05454 | 0.00249 | 0.55484 | 0.03804 | 0.07378 | 0.00378 | 394 | 102 | 459 | 23 | -17 |
| 76 | 353921 | 75 | 0.07894 | 0.00114 | 2.17683 | 0.12033 | 0.19999 | 0.01067 | 1171 | 29 | 1175 | 57 | 0 |
| 79 | 96713 | 57 | 0.07165 | 0.00171 | 1.59846 | 0.09582 | 0.16181 | 0.00890 | 976 | 49 | 967 | 49 | 1 |
| 80 | 69167 | 76 | 0.05405 | 0.00055 | 0.51428 | 0.01937 | 0.06901 | 0.00250 | 373 | 23 | 430 | 15 | -16 |
| 81 | 117030 | 37 | 0.06555 | 0.00108 | 0.94641 | 0.08323 | 0.10471 | 0.00905 | 792 | 34 | 642 | 53 | 20 |
| 82 | 64313 | 68 | 0.05393 | 0.00071 | 0.50595 | 0.01917 | 0.06804 | 0.00242 | 368 | 30 | 424 | 15 | -16 |
| 83 | 35631 | 31 | 0.07160 | 0.00145 | 1.64387 | 0.09257 | 0.16652 | 0.00875 | 975 | 41 | 993 | 48 | -2 |
| 84 | 75621 | 25 | 0.09983 | 0.00149 | 3.59115 | 0.20379 | 0.26089 | 0.01428 | 1621 | 28 | 1494 | 73 | 9 |
| 85 | 129947 | 40 | 0.07397 | 0.00113 | 1.84332 | 0.11975 | 0.18075 | 0.01141 | 1041 | 31 | 1071 | 62 | -3 |
| Sample 09MILAN01 - Milan member | | | | | | | | | | | | | |
| 4 | 48218 | 7 | 0.06797 | 0.00208 | 1.61491 | 0.08457 | 0.17231 | 0.00733 | 868 | 32 | 1025 | 40 | -20 |
| 7 | 56022 | 10 | 0.06439 | 0.00190 | 1.36875 | 0.06499 | 0.15417 | 0.00574 | 754 | 31 | 924 | 32 | -24 |
| 11 | 296610 | 51 | 0.10253 | 0.00257 | 4.00416 | 0.17315 | 0.28325 | 0.00998 | 1670 | 23 | 1608 | 50 | 4 |
| 12 | 44914 | 35 | 0.07954 | 0.00259 | 2.35102 | 0.17169 | 0.21436 | 0.01402 | 1186 | 32 | 1252 | 74 | -6 |
| 18 | 106628 | 42 | 0.05385 | 0.00142 | 0.50098 | 0.02210 | 0.06747 | 0.00239 | 365 | 30 | 421 | 14 | -16 |
| 19 | 44259 | 43 | 0.06801 | 0.00206 | 1.51794 | 0.06966 | 0.16188 | 0.00558 | 869 | 31 | 967 | 31 | -12 |
| 20 | 95147 | 25 | 0.10008 | 0.00256 | 3.79217 | 0.18058 | 0.27481 | 0.01104 | 1626 | 24 | 1565 | 56 | 4 |
| 21 | 163971 | 42 | 0.07696 | 0.00195 | 1.95923 | 0.10535 | 0.18465 | 0.00875 | 1120 | 25 | 1092 | 47 | 3 |
| 26 | 57092 | 30 | 0.06884 | 0.00203 | 1.43466 | 0.07576 | 0.15115 | 0.00662 | 894 | 30 | 907 | 37 | -2 |
| 27 | 113987 | 51 | 0.07177 | 0.00186 | 1.54332 | 0.07926 | 0.15595 | 0.00691 | 979 | 26 | 934 | 38 | 5 |
| 29 | 30714 | 48 | 0.07445 | 0.00218 | 2.11174 | 0.11069 | 0.20572 | 0.00895 | 1054 | 29 | 1206 | 48 | -16 |
| 30 | 65406 | 52 | 0.08818 | 0.00242 | 2.77726 | 0.12364 | 0.22843 | 0.00800 | 1386 | 26 | 1326 | 42 | 5 |
| 32 | 45752 | 47 | 0.06791 | 0.00211 | 1.53355 | 0.07378 | 0.16377 | 0.00602 | 866 | 32 | 978 | 33 | -14 |
| 33 | 58553 | 63 | 0.09858 | 0.00273 | 3.83108 | 0.21251 | 0.28186 | 0.01355 | 1597 | 26 | 1601 | 68 | 0 |
| 34 | 75633 | 58 | 0.09989 | 0.00261 | 3.74227 | 0.22601 | 0.27171 | 0.01480 | 1622 | 24 | 1549 | 75 | 5 |
| 35 | 28980 | 112 | 0.07410 | 0.00180 | 1.61373 | 0.24978 | 0.15796 | 0.02415 | 1044 | 49 | 945 | 133 | 10 |
| 36 | 54000 | 37 | 0.05351 | 0.00114 | 0.49636 | 0.01986 | 0.06727 | 0.00227 | 351 | 48 | 420 | 14 | -20 |

Appendix 1
*(continued)*

| Grain # | $^{206}Pb$ (cps) | $^{204}Pb$ (cps) | $\frac{^{207}Pb}{^{206}Pb}$ | 2σ | $\frac{^{207}Pb}{^{235}U}$ | 2σ | $\frac{^{206}Pb}{^{238}U}$ | 2σ | age (Ma) $\frac{^{207}Pb}{^{206}Pb}$ | 2σ | age (Ma) $\frac{^{206}Pb}{^{238}U}$ | 2σ | disc. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample 09MILAN01 - Milan member | | | | | | | | | | | | | |
| 37 | 37931 | 98 | 0.07224 | 0.00125 | 1.75355 | 0.26411 | 0.17605 | 0.02634 | 993 | 35 | 1045 | 143 | -6 |
| 39 | 78701 | 80 | 0.07261 | 0.00113 | 1.69946 | 0.25692 | 0.16976 | 0.02553 | 1003 | 32 | 1011 | 139 | -1 |
| 41 | 65246 | 48 | 0.08384 | 0.00142 | 2.45143 | 0.25701 | 0.21207 | 0.02194 | 1289 | 33 | 1240 | 116 | 4 |
| 42 | 45262 | 53 | 0.07201 | 0.00130 | 1.66831 | 0.17314 | 0.16802 | 0.01717 | 986 | 37 | 1001 | 94 | -2 |
| 43 | 36835 | 47 | 0.06805 | 0.00114 | 1.42344 | 0.14684 | 0.15172 | 0.01544 | 870 | 35 | 911 | 86 | -5 |
| 44 | 64539 | 51 | 0.07184 | 0.00116 | 1.58044 | 0.16382 | 0.15955 | 0.01633 | 981 | 33 | 954 | 90 | 3 |
| 45 | 138238 | 63 | 0.05554 | 0.00060 | 0.50643 | 0.02082 | 0.06613 | 0.00262 | 434 | 24 | 413 | 16 | 5 |
| 46 | 55111 | 51 | 0.09101 | 0.00137 | 2.94837 | 0.31024 | 0.23495 | 0.02447 | 1447 | 29 | 1360 | 126 | 7 |
| 47 | 127955 | 71 | 0.07261 | 0.00112 | 1.60381 | 0.16561 | 0.16019 | 0.01636 | 1003 | 31 | 958 | 90 | 5 |
| 48 | 55584 | 72 | 0.05604 | 0.00131 | 0.53741 | 0.02239 | 0.06955 | 0.00240 | 454 | 52 | 433 | 14 | 5 |
| 49 | 85751 | 75 | 0.05460 | 0.00070 | 0.51715 | 0.01901 | 0.06870 | 0.00237 | 396 | 29 | 428 | 14 | -9 |
| 50 | 44062 | 50 | 0.05316 | 0.00131 | 0.48218 | 0.05177 | 0.06578 | 0.00687 | 336 | 56 | 411 | 41 | -23 |
| 51 | 37581 | 70 | 0.08105 | 0.00450 | 1.92124 | 0.21440 | 0.17191 | 0.01664 | 1223 | 109 | 1023 | 91 | 18 |
| 52 | 45513 | 47 | 0.05335 | 0.00085 | 0.47422 | 0.04571 | 0.06447 | 0.00613 | 344 | 36 | 403 | 37 | -18 |
| 53 | 40314 | 60 | 0.05469 | 0.00141 | 0.50114 | 0.02241 | 0.06646 | 0.00242 | 399 | 58 | 415 | 15 | -4 |
| 54 | 15145 | 43 | 0.05390 | 0.00449 | 0.51559 | 0.06416 | 0.06938 | 0.00641 | 367 | 188 | 432 | 39 | -19 |
| 55 | 22297 | 68 | 0.05441 | 0.00337 | 0.48625 | 0.03570 | 0.06482 | 0.00255 | 388 | 139 | 405 | 15 | -5 |
| 56 | 66833 | 95 | 0.05569 | 0.00198 | 0.51697 | 0.02595 | 0.06733 | 0.00238 | 440 | 79 | 420 | 14 | 5 |
| 58 | 17542 | 64 | 0.07791 | 0.00515 | 1.95753 | 0.22157 | 0.18222 | 0.01675 | 1145 | 131 | 1079 | 91 | 6 |
| 59 | 41116 | 47 | 0.07324 | 0.00160 | 1.66857 | 0.15628 | 0.16523 | 0.01505 | 1021 | 44 | 986 | 83 | 4 |
| 60 | 51574 | 38 | 0.07410 | 0.00132 | 1.65307 | 0.15398 | 0.16179 | 0.01479 | 1044 | 36 | 967 | 82 | 8 |
| 61 | 14574 | 46 | 0.06771 | 0.00287 | 1.71992 | 0.08676 | 0.18424 | 0.00503 | 860 | 88 | 1090 | 27 | -29 |
| 62 | 32389 | 38 | 0.05366 | 0.00123 | 0.49618 | 0.01676 | 0.06706 | 0.00166 | 357 | 52 | 418 | 10 | -18 |
| 64 | 22469 | 28 | 0.06849 | 0.00135 | 1.54099 | 0.04819 | 0.16318 | 0.00395 | 883 | 41 | 974 | 22 | -11 |
| 65 | 25123 | 40 | 0.07129 | 0.00178 | 1.93033 | 0.06365 | 0.19638 | 0.00424 | 966 | 51 | 1156 | 23 | -22 |
| 67 | 34778 | 198 | 0.05757 | 0.00332 | 0.52521 | 0.03840 | 0.06617 | 0.00297 | 513 | 127 | 413 | 18 | 20 |
| 68 | 37582 | 46 | 0.07438 | 0.00202 | 1.72468 | 0.05927 | 0.16817 | 0.00354 | 1052 | 55 | 1002 | 20 | 5 |
| 69 | 88669 | 37 | 0.05572 | 0.00105 | 0.59390 | 0.01889 | 0.07731 | 0.00198 | 441 | 42 | 480 | 12 | -9 |
| 70 | 31319 | 35 | 0.06778 | 0.00158 | 1.65567 | 0.05081 | 0.17716 | 0.00354 | 862 | 48 | 1051 | 19 | -24 |
| 71 | 65931 | 47 | 0.08206 | 0.00136 | 2.31556 | 0.14984 | 0.20465 | 0.01280 | 1247 | 32 | 1200 | 68 | 4 |
| 72 | 66805 | 60 | 0.05512 | 0.00096 | 0.48865 | 0.02618 | 0.06430 | 0.00326 | 417 | 39 | 402 | 20 | 4 |
| 73 | 46113 | 59 | 0.05274 | 0.00106 | 0.45988 | 0.02202 | 0.06324 | 0.00275 | 318 | 46 | 395 | 17 | -25 |
| 74 | 104009 | 97 | 0.05638 | 0.00120 | 0.52602 | 0.03015 | 0.06767 | 0.00360 | 467 | 47 | 422 | 22 | 10 |
| 75 | 32451 | 61 | 0.05454 | 0.00249 | 0.55484 | 0.03804 | 0.07378 | 0.00378 | 394 | 102 | 459 | 23 | -17 |
| 76 | 353921 | 75 | 0.07894 | 0.00114 | 2.17683 | 0.12033 | 0.19999 | 0.01067 | 1171 | 29 | 1175 | 57 | 0 |
| 79 | 96713 | 57 | 0.07165 | 0.00171 | 1.59846 | 0.09582 | 0.16181 | 0.00890 | 976 | 49 | 967 | 49 | 1 |
| 80 | 69167 | 76 | 0.05405 | 0.00055 | 0.51428 | 0.01937 | 0.06901 | 0.00250 | 373 | 23 | 430 | 15 | -16 |
| 81 | 117030 | 37 | 0.06555 | 0.00108 | 0.94641 | 0.08323 | 0.10471 | 0.00905 | 792 | 34 | 642 | 53 | 20 |
| 82 | 64313 | 68 | 0.05393 | 0.00071 | 0.50595 | 0.01917 | 0.06804 | 0.00242 | 368 | 30 | 424 | 15 | -16 |
| 83 | 35631 | 31 | 0.07160 | 0.00145 | 1.64387 | 0.09257 | 0.16652 | 0.00875 | 975 | 41 | 993 | 48 | -2 |
| 84 | 75621 | 25 | 0.09983 | 0.00149 | 3.59115 | 0.20379 | 0.26089 | 0.01428 | 1621 | 28 | 1494 | 73 | 9 |
| 85 | 129947 | 40 | 0.07397 | 0.00113 | 1.84332 | 0.11975 | 0.18075 | 0.01141 | 1041 | 31 | 1071 | 62 | -3 |
| Sample 09MILAN01 - Milan member | | | | | | | | | | | | | |
| 4 | 48218 | 7 | 0.06797 | 0.00208 | 1.61491 | 0.08457 | 0.17231 | 0.00733 | 868 | 32 | 1025 | 40 | -20 |
| 7 | 56022 | 10 | 0.06439 | 0.00190 | 1.36875 | 0.06499 | 0.15417 | 0.00574 | 754 | 31 | 924 | 32 | -24 |
| 11 | 296610 | 51 | 0.10253 | 0.00257 | 4.00416 | 0.17315 | 0.28325 | 0.00998 | 1670 | 23 | 1608 | 50 | 4 |
| 12 | 44914 | 35 | 0.07954 | 0.00259 | 2.35102 | 0.17169 | 0.21436 | 0.01402 | 1186 | 32 | 1252 | 74 | -6 |
| 18 | 106628 | 42 | 0.05385 | 0.00142 | 0.50098 | 0.02210 | 0.06747 | 0.00239 | 365 | 30 | 421 | 14 | -16 |
| 19 | 44259 | 43 | 0.06801 | 0.00206 | 1.51794 | 0.06966 | 0.16188 | 0.00558 | 869 | 31 | 967 | 31 | -12 |
| 20 | 95147 | 25 | 0.10008 | 0.00256 | 3.79217 | 0.18058 | 0.27481 | 0.01104 | 1626 | 24 | 1565 | 56 | 4 |
| 21 | 163971 | 42 | 0.07696 | 0.00195 | 1.95923 | 0.10535 | 0.18465 | 0.00875 | 1120 | 25 | 1092 | 47 | 3 |
| 26 | 57092 | 30 | 0.06884 | 0.00203 | 1.43466 | 0.07576 | 0.15115 | 0.00662 | 894 | 30 | 907 | 37 | -2 |
| 27 | 113987 | 51 | 0.07177 | 0.00186 | 1.54332 | 0.07926 | 0.15595 | 0.00691 | 979 | 26 | 934 | 38 | 5 |
| 29 | 30714 | 48 | 0.07445 | 0.00218 | 2.11174 | 0.11069 | 0.20572 | 0.00895 | 1054 | 29 | 1206 | 48 | -16 |
| 30 | 65406 | 52 | 0.08818 | 0.00242 | 2.77726 | 0.12364 | 0.22843 | 0.00800 | 1386 | 26 | 1326 | 42 | 5 |
| 32 | 45752 | 47 | 0.06791 | 0.00211 | 1.53355 | 0.07378 | 0.16377 | 0.00602 | 866 | 32 | 978 | 33 | -14 |
| 33 | 58553 | 63 | 0.09858 | 0.00273 | 3.83108 | 0.21251 | 0.28186 | 0.01355 | 1597 | 26 | 1601 | 68 | 0 |
| 34 | 75633 | 58 | 0.09989 | 0.00261 | 3.74227 | 0.22601 | 0.27171 | 0.01480 | 1622 | 24 | 1549 | 75 | 5 |
| 36 | 54753 | 56 | 0.07094 | 0.00201 | 1.75280 | 0.08569 | 0.17919 | 0.00715 | 956 | 29 | 1063 | 39 | -12 |
| 38 | 51289 | 77 | 0.06919 | 0.00197 | 1.55639 | 0.06831 | 0.16315 | 0.00545 | 904 | 29 | 974 | 30 | -8 |
| 43 | 163876 | 66 | 0.05471 | 0.00140 | 0.52415 | 0.02386 | 0.06948 | 0.00262 | 400 | 29 | 433 | 16 | -8 |
| 45 | 102350 | 70 | 0.07224 | 0.00192 | 1.72275 | 0.08627 | 0.17296 | 0.00734 | 993 | 27 | 1028 | 40 | -4 |
| 46 | 148705 | 73 | 0.16671 | 0.00418 | 11.06694 | 0.65409 | 0.48146 | 0.02577 | 2525 | 21 | 2534 | 111 | 0 |
| 47 | 44762 | 59 | 0.08477 | 0.00245 | 2.74620 | 0.14691 | 0.23495 | 0.01058 | 1310 | 28 | 1360 | 55 | -4 |
| 48 | 56174 | 49 | 0.11084 | 0.00286 | 4.81771 | 0.26800 | 0.31523 | 0.01554 | 1813 | 23 | 1766 | 76 | 3 |
| 49 | 544493 | 63 | 0.07606 | 0.00191 | 1.95241 | 0.09755 | 0.18618 | 0.00804 | 1097 | 25 | 1101 | 44 | 0 |
| 54 | 44311 | 11 | 0.06625 | 0.00205 | 1.47208 | 0.08269 | 0.16114 | 0.00756 | 814 | 32 | 963 | 42 | -20 |
| 56 | 83238 | 23 | 0.20171 | 0.00511 | 15.80533 | 1.03613 | 0.56831 | 0.03436 | 2840 | 21 | 2901 | 140 | -3 |
| 57 | 143060 | 18 | 0.19755 | 0.00495 | 14.50804 | 0.73413 | 0.53264 | 0.02342 | 2806 | 20 | 2753 | 98 | 2 |
| 59 | 85099 | 14 | 0.08299 | 0.00227 | 2.35490 | 0.11071 | 0.20579 | 0.00787 | 1269 | 27 | 1206 | 42 | 5 |
| 60 | 84452 | 16 | 0.07902 | 0.00210 | 2.24020 | 0.11382 | 0.20562 | 0.00891 | 1173 | 26 | 1205 | 47 | -3 |
| 61 | 29097 | 54 | 0.05714 | 0.00114 | 0.47520 | 0.05528 | 0.06032 | 0.00691 | 497 | 22 | 378 | 42 | 25 |
| 62 | 35559 | 59 | 0.05747 | 0.00081 | 0.48183 | 0.04511 | 0.06081 | 0.00563 | 510 | 16 | 381 | 34 | 26 |
| 63 | 68317 | 52 | 0.08186 | 0.00106 | 1.82435 | 0.17980 | 0.16164 | 0.01579 | 1242 | 13 | 966 | 87 | 24 |
| 65 | 321875 | 44 | 0.07716 | 0.00071 | 1.70378 | 0.14343 | 0.16015 | 0.01340 | 1125 | 9 | 958 | 74 | 16 |

Appendix 1

*(continued)*

| | | | | | | | | | age (Ma) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Grain # | $^{206}$Pb (cps) | $^{204}$Pb (cps) | $\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$ | 2σ | $\frac{^{207}\text{Pb}}{^{235}\text{U}}$ | 2σ | $\frac{^{206}\text{Pb}}{^{238}\text{U}}$ | 2σ | $\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$ | 2σ | $\frac{^{206}\text{Pb}}{^{238}\text{U}}$ | 2σ | disc. |
| Sample 09MILAN01 - Milan member | | | | | | | | | | | | | |
| 66 | 57052 | 48 | 0.08080 | 0.00094 | 1.83361 | 0.17655 | 0.16458 | 0.01573 | 1217 | 11 | 982 | 86 | 21 |
| 67 | 17032 | 46 | 0.05598 | 0.00109 | 0.47110 | 0.04168 | 0.06104 | 0.00527 | 451 | 22 | 382 | 32 | 16 |
| 68 | 40264 | 40 | 0.07372 | 0.00108 | 1.40940 | 0.12688 | 0.13866 | 0.01231 | 1034 | 15 | 837 | 69 | 20 |
| 69 | 14295 | 41 | 0.05673 | 0.00131 | 0.48116 | 0.04201 | 0.06151 | 0.00518 | 481 | 25 | 385 | 31 | 21 |
| 70 | 149899 | 51 | 0.07561 | 0.00073 | 1.55505 | 0.14087 | 0.14916 | 0.01343 | 1085 | 10 | 896 | 75 | 19 |
| 71 | 182656 | 62 | 0.08326 | 0.00075 | 2.43740 | 0.21944 | 0.21231 | 0.01902 | 1275 | 9 | 1241 | 100 | 3 |
| 72 | 51064 | 70 | 0.07344 | 0.00079 | 1.77209 | 0.18350 | 0.17500 | 0.01802 | 1026 | 11 | 1040 | 98 | -1 |
| 73 | 7440 | 64 | 0.06068 | 0.00247 | 0.71752 | 0.06361 | 0.08577 | 0.00675 | 628 | 44 | 530 | 40 | 16 |
| 74 | 45352 | 80 | 0.05702 | 0.00064 | 0.64549 | 0.06847 | 0.08211 | 0.00866 | 492 | 12 | 509 | 51 | -3 |
| 75 | 68189 | 82 | 0.07527 | 0.00080 | 1.93438 | 0.17232 | 0.18639 | 0.01649 | 1076 | 11 | 1102 | 89 | -3 |
| 76 | 26667 | 77 | 0.07613 | 0.00111 | 1.99289 | 0.14399 | 0.18986 | 0.01343 | 1098 | 15 | 1121 | 72 | -2 |
| 77 | 49302 | 96 | 0.05570 | 0.00058 | 0.60766 | 0.05375 | 0.07912 | 0.00695 | 441 | 12 | 491 | 41 | -12 |
| 78 | 26022 | 91 | 0.05602 | 0.00091 | 0.58946 | 0.05283 | 0.07632 | 0.00673 | 453 | 18 | 474 | 40 | -5 |
| 79 | 5087 | 99 | 0.06065 | 0.00301 | 0.69477 | 0.06138 | 0.08308 | 0.00607 | 627 | 54 | 514 | 36 | 19 |
| 80 | 88792 | 111 | 0.07372 | 0.00068 | 1.73764 | 0.16947 | 0.17096 | 0.01660 | 1034 | 9 | 1017 | 91 | 2 |
| 81 | 35043 | 120 | 0.05821 | 0.00110 | 0.53089 | 0.03814 | 0.06614 | 0.00459 | 538 | 21 | 413 | 28 | 24 |
| 82 | 47570 | 118 | 0.07324 | 0.00086 | 1.35318 | 0.10464 | 0.13400 | 0.01024 | 1021 | 12 | 811 | 58 | 22 |
| 83 | 153809 | 123 | 0.09296 | 0.00084 | 2.68156 | 0.22608 | 0.20921 | 0.01754 | 1487 | 9 | 1225 | 93 | 19 |
| 84 | 168886 | 130 | 0.05536 | 0.00052 | 0.42780 | 0.03424 | 0.05604 | 0.00445 | 427 | 11 | 352 | 27 | 18 |
| Sample 09MILAN01b grain set | | | | | | | | | | | | | |
| 1 | 71754 | 73 | 0.05560 | 0.00068 | 0.51704 | 0.02334 | 0.06744 | 0.00293 | 436 | 27 | 421 | 18 | 4 |
| 2 | 126039 | 109 | 0.05536 | 0.00058 | 0.47090 | 0.01914 | 0.06170 | 0.00242 | 427 | 24 | 386 | 15 | 10 |
| 3 | 73036 | 73 | 0.05609 | 0.00051 | 0.52470 | 0.02315 | 0.06784 | 0.00293 | 456 | 20 | 423 | 18 | 7 |
| 4 | 116715 | 91 | 0.05451 | 0.00050 | 0.47020 | 0.02057 | 0.06256 | 0.00268 | 392 | 20 | 391 | 16 | 0 |
| 5 | 23653 | 95 | 0.05526 | 0.00142 | 0.47900 | 0.02452 | 0.06287 | 0.00278 | 423 | 57 | 393 | 17 | 7 |
| 6 | 211815 | 111 | 0.05467 | 0.00044 | 0.47159 | 0.01723 | 0.06256 | 0.00223 | 399 | 18 | 391 | 14 | 2 |
| 7 | 113250 | 103 | 0.05483 | 0.00049 | 0.47204 | 0.01795 | 0.06244 | 0.00231 | 405 | 20 | 390 | 14 | 4 |
| 8 | 174877 | 98 | 0.05447 | 0.00043 | 0.47322 | 0.01787 | 0.06301 | 0.00233 | 390 | 18 | 394 | 14 | -1 |
| 9 | 86807 | 109 | 0.05473 | 0.00044 | 0.46472 | 0.01943 | 0.06158 | 0.00253 | 401 | 18 | 385 | 15 | 4 |
| 10 | 109151 | 97 | 0.05485 | 0.00050 | 0.48483 | 0.01829 | 0.06410 | 0.00235 | 406 | 20 | 401 | 14 | 1 |
| 11 | 57076 | 126 | 0.05677 | 0.00065 | 0.53980 | 0.01927 | 0.06897 | 0.00233 | 482 | 25 | 430 | 14 | 11 |
| 12 | 161856 | 116 | 0.05448 | 0.00039 | 0.47089 | 0.01774 | 0.06269 | 0.00232 | 391 | 16 | 392 | 14 | 0 |
| 13 | 92964 | 107 | 0.05614 | 0.00047 | 0.52930 | 0.02275 | 0.06839 | 0.00288 | 458 | 18 | 426 | 17 | 7 |
| 14 | 30700 | 100 | 0.05585 | 0.00084 | 0.51351 | 0.02164 | 0.06668 | 0.00262 | 446 | 34 | 416 | 16 | 7 |
| 15 | 136124 | 119 | 0.07715 | 0.00069 | 1.86420 | 0.08562 | 0.17524 | 0.00789 | 1125 | 18 | 1041 | 43 | 8 |
| 16 | 153361 | 88 | 0.05437 | 0.00041 | 0.45990 | 0.01660 | 0.06135 | 0.00217 | 386 | 17 | 384 | 13 | 1 |
| 17 | 82008 | 130 | 0.05691 | 0.00054 | 0.56017 | 0.02890 | 0.07139 | 0.00362 | 488 | 21 | 445 | 22 | 9 |
| 19 | 227467 | 90 | 0.05469 | 0.00041 | 0.46823 | 0.02153 | 0.06209 | 0.00282 | 400 | 17 | 388 | 17 | 3 |
| 20 | 35386 | 102 | 0.05428 | 0.00064 | 0.45326 | 0.01697 | 0.06056 | 0.00215 | 383 | 26 | 379 | 13 | 1 |
| 21 | 90252 | 101 | 0.05594 | 0.00050 | 0.54016 | 0.02344 | 0.07003 | 0.00298 | 450 | 20 | 436 | 18 | 3 |
| 22 | 204799 | 128 | 0.05452 | 0.00040 | 0.45269 | 0.01900 | 0.06022 | 0.00249 | 392 | 16 | 377 | 15 | 4 |
| 23 | 206693 | 110 | 0.06008 | 0.00057 | 0.67209 | 0.02574 | 0.08113 | 0.00301 | 607 | 21 | 503 | 18 | 18 |
| 24 | 69684 | 130 | 0.07338 | 0.00059 | 1.63709 | 0.05792 | 0.16180 | 0.00557 | 1025 | 16 | 967 | 31 | 6 |
| 25 | 38166 | 123 | 0.05446 | 0.00045 | 0.45548 | 0.01658 | 0.06065 | 0.00215 | 390 | 18 | 380 | 13 | 3 |
| 26 | 47323 | 130 | 0.05655 | 0.00075 | 0.52895 | 0.02230 | 0.06784 | 0.00272 | 474 | 29 | 423 | 16 | 11 |
| 27 | 245140 | 119 | 0.07433 | 0.00050 | 1.70667 | 0.09897 | 0.16654 | 0.00959 | 1050 | 14 | 993 | 53 | 6 |
| 28 | 125420 | 139 | 0.05497 | 0.00047 | 0.47654 | 0.01825 | 0.06287 | 0.00235 | 411 | 19 | 393 | 14 | 5 |
| 29 | 262781 | 118 | 0.07410 | 0.00054 | 1.67742 | 0.05895 | 0.16418 | 0.00564 | 1044 | 15 | 980 | 31 | 7 |
| 30 | 358233 | 110 | 0.07174 | 0.00050 | 1.54307 | 0.06077 | 0.15601 | 0.00605 | 978 | 14 | 935 | 34 | 5 |
| Sample 09MILAN02 - Milan member | | | | | | | | | | | | | |
| 2 | 27667 | 65 | 0.07776 | 0.00102 | 2.12977 | 0.12602 | 0.19864 | 0.01146 | 1141 | 13 | 1168 | 61 | -3 |
| 3 | 56045 | 65 | 0.07394 | 0.00069 | 1.84293 | 0.13042 | 0.18078 | 0.01268 | 1040 | 9 | 1071 | 69 | -3 |
| 4 | 285428 | 64 | 0.16868 | 0.00130 | 11.73750 | 0.67463 | 0.50467 | 0.02875 | 2545 | 6 | 2634 | 122 | -4 |
| 5 | 41568 | 75 | 0.07849 | 0.00085 | 2.10336 | 0.13246 | 0.19435 | 0.01206 | 1159 | 11 | 1145 | 65 | 1 |
| 6 | 19651 | 82 | 0.07800 | 0.00143 | 2.16927 | 0.12861 | 0.20170 | 0.01137 | 1147 | 18 | 1184 | 61 | -4 |
| 7 | 38715 | 62 | 0.05561 | 0.00070 | 0.51557 | 0.02886 | 0.06724 | 0.00367 | 437 | 14 | 420 | 22 | 4 |
| 8 | 29772 | 62 | 0.05565 | 0.00074 | 0.53113 | 0.02934 | 0.06922 | 0.00371 | 438 | 15 | 431 | 22 | 2 |
| 9 | 27705 | 56 | 0.07609 | 0.00098 | 1.83292 | 0.11263 | 0.17471 | 0.01050 | 1097 | 13 | 1038 | 57 | 6 |
| 10 | 41808 | 67 | 0.05478 | 0.00062 | 0.48350 | 0.03248 | 0.06401 | 0.00424 | 403 | 13 | 400 | 26 | 1 |
| 11 | 29300 | 30 | 0.07251 | 0.00094 | 1.67506 | 0.10970 | 0.16754 | 0.01076 | 1000 | 13 | 999 | 59 | 0 |
| 12 | 53155 | 34 | 0.08829 | 0.00081 | 2.78404 | 0.16674 | 0.22870 | 0.01354 | 1389 | 9 | 1328 | 71 | 5 |
| 13 | 51166 | 28 | 0.05496 | 0.00062 | 0.51729 | 0.03002 | 0.06826 | 0.00389 | 411 | 13 | 426 | 23 | -4 |
| 14 | 46278 | 17 | 0.05539 | 0.00072 | 0.53247 | 0.02797 | 0.06972 | 0.00355 | 428 | 14 | 434 | 21 | -2 |
| 16 | 74903 | 14 | 0.05967 | 0.00060 | 0.82267 | 0.04547 | 0.09999 | 0.00543 | 592 | 11 | 614 | 32 | -4 |
| 17 | 70194 | 14 | 0.07295 | 0.00073 | 1.39906 | 0.07333 | 0.13910 | 0.00716 | 1012 | 10 | 840 | 40 | 18 |
| 18 | 602632 | 15 | 0.07583 | 0.00059 | 1.95871 | 0.12339 | 0.18734 | 0.01171 | 1091 | 8 | 1107 | 63 | -2 |
| 19 | 15702 | 10 | 0.07172 | 0.00141 | 1.74816 | 0.09833 | 0.17677 | 0.00932 | 978 | 20 | 1049 | 51 | -8 |
| 20 | 80164 | 14 | 0.05593 | 0.00051 | 0.50492 | 0.03017 | 0.06548 | 0.00387 | 450 | 10 | 409 | 23 | 9 |
| 21 | 29258 | 40 | 0.05532 | 0.00074 | 0.54553 | 0.03001 | 0.07152 | 0.00381 | 425 | 15 | 445 | 23 | -5 |
| 22 | 8653 | 48 | 0.07144 | 0.00211 | 1.81241 | 0.12355 | 0.18400 | 0.01130 | 970 | 30 | 1089 | 61 | -13 |
| 23 | 62479 | 36 | 0.07425 | 0.00070 | 1.75472 | 0.11611 | 0.17141 | 0.01123 | 1048 | 10 | 1020 | 61 | 3 |
| 24 | 66592 | 46 | 0.10356 | 0.00096 | 4.14042 | 0.23486 | 0.28997 | 0.01623 | 1689 | 9 | 1641 | 81 | 3 |
| 25 | 63962 | 51 | 0.05999 | 0.00064 | 0.80154 | 0.04417 | 0.09691 | 0.00524 | 603 | 11 | 596 | 31 | 1 |
| 26 | 25184 | 48 | 0.07434 | 0.00094 | 1.79198 | 0.10465 | 0.17483 | 0.00997 | 1051 | 13 | 1039 | 54 | 1 |

Appendix 1
*(continued)*

| Grain # | $^{206}Pb$ (cps) | $^{204}Pb$ (cps) | $\frac{^{207}Pb}{^{206}Pb}$ | 2σ | $\frac{^{207}Pb}{^{235}U}$ | 2σ | age (Ma) $\frac{^{206}Pb}{^{238}U}$ | 2σ | $\frac{^{207}Pb}{^{206}Pb}$ | 2σ | $\frac{^{206}Pb}{^{238}U}$ | 2σ | disc. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample 09MILAN02 - Milan member | | | | | | | | | | | | | |
| 27 | 40156 | 50 | 0.07421 | 0.00083 | 1.69303 | 0.11188 | 0.16547 | 0.01078 | 1047 | 11 | 987 | 59 | 6 |
| 28 | 246542 | 67 | 0.18226 | 0.00142 | 12.73073 | 0.79226 | 0.50659 | 0.03128 | 2674 | 6 | 2642 | 132 | 1 |
| 29 | 28378 | 54 | 0.05589 | 0.00079 | 0.54593 | 0.03447 | 0.07085 | 0.00436 | 448 | 16 | 441 | 26 | 2 |
| 30 | 4003 | 48 | 0.05811 | 0.00374 | 0.67585 | 0.06095 | 0.08436 | 0.00533 | 534 | 70 | 522 | 32 | 2 |
| 31 | 63225 | 53 | 0.07427 | 0.00065 | 1.77475 | 0.09855 | 0.17331 | 0.00950 | 1049 | 9 | 1030 | 52 | 2 |
| 32 | 18920 | 49 | 0.07861 | 0.00131 | 2.42358 | 0.16720 | 0.22360 | 0.01497 | 1162 | 16 | 1301 | 78 | -13 |
| 33 | 23674 | 54 | 0.08676 | 0.00109 | 2.59857 | 0.16884 | 0.21722 | 0.01385 | 1355 | 12 | 1267 | 73 | 7 |
| 34 | 17417 | 61 | 0.07419 | 0.00138 | 1.92703 | 0.13902 | 0.18838 | 0.01313 | 1047 | 19 | 1113 | 71 | -7 |
| 35 | 9555 | 47 | 0.05801 | 0.00185 | 0.62263 | 0.03740 | 0.07784 | 0.00396 | 530 | 35 | 483 | 24 | 9 |
| 36 | 203354 | 54 | 0.07713 | 0.00064 | 1.93710 | 0.12100 | 0.18215 | 0.01128 | 1125 | 8 | 1079 | 61 | 4 |
| 37 | 169555 | 42 | 0.11170 | 0.00092 | 4.65193 | 0.26195 | 0.30204 | 0.01682 | 1827 | 7 | 1701 | 83 | 8 |
| 38 | 43779 | 44 | 0.07705 | 0.00086 | 1.93031 | 0.14312 | 0.18169 | 0.01332 | 1123 | 11 | 1076 | 72 | 4 |
| 39 | 14398 | 55 | 0.07244 | 0.00123 | 1.77575 | 0.10755 | 0.17779 | 0.01034 | 998 | 17 | 1055 | 56 | -6 |
| 40 | 220862 | 67 | 0.11343 | 0.00092 | 4.99399 | 0.29453 | 0.31931 | 0.01865 | 1855 | 7 | 1786 | 90 | 4 |
| 41 | 96488 | 77 | 0.05546 | 0.00052 | 0.55121 | 0.03129 | 0.07209 | 0.00404 | 431 | 10 | 449 | 24 | -4 |
| 42 | 330588 | 90 | 0.17209 | 0.00135 | 11.37042 | 0.83512 | 0.47921 | 0.03500 | 2578 | 7 | 2524 | 151 | 3 |
| 43 | 42266 | 74 | 0.07388 | 0.00086 | 1.71539 | 0.10949 | 0.16839 | 0.01057 | 1038 | 12 | 1003 | 58 | 4 |
| 44 | 81972 | 72 | 0.07891 | 0.00071 | 2.02097 | 0.11476 | 0.18575 | 0.01041 | 1170 | 9 | 1098 | 56 | 7 |
| 45 | 59516 | 88 | 0.07428 | 0.00074 | 1.72116 | 0.10604 | 0.16806 | 0.01022 | 1049 | 10 | 1001 | 56 | 5 |
| 46 | 30183 | 90 | 0.07166 | 0.00096 | 1.53737 | 0.09953 | 0.15559 | 0.00986 | 976 | 14 | 932 | 55 | 5 |
| 47 | 58800 | 83 | 0.07321 | 0.00086 | 1.61731 | 0.10366 | 0.16022 | 0.01009 | 1020 | 12 | 958 | 56 | 7 |
| 48 | 57235 | 80 | 0.18521 | 0.00159 | 11.82873 | 0.69321 | 0.46320 | 0.02685 | 2700 | 7 | 2454 | 117 | 11 |
| 49 | 74854 | 81 | 0.07433 | 0.00070 | 1.72201 | 0.10193 | 0.16803 | 0.00982 | 1050 | 9 | 1001 | 54 | 5 |
| 50 | 62055 | 75 | 0.07334 | 0.00077 | 1.60998 | 0.09326 | 0.15922 | 0.00907 | 1023 | 11 | 952 | 50 | 7 |
| 51 | 31741 | 64 | 0.06859 | 0.00136 | 1.41411 | 0.14716 | 0.14954 | 0.01527 | 886 | 21 | 898 | 85 | -1 |
| 54 | 113694 | 93 | 0.05825 | 0.00068 | 0.69204 | 0.06753 | 0.08617 | 0.00835 | 539 | 13 | 533 | 49 | 1 |
| 55 | 112048 | 107 | 0.05543 | 0.00049 | 0.52567 | 0.04220 | 0.06878 | 0.00549 | 430 | 10 | 429 | 33 | 0 |
| 56 | 48093 | 114 | 0.05302 | 0.00071 | 0.48329 | 0.05099 | 0.06611 | 0.00692 | 330 | 15 | 413 | 42 | -26 |
| 57 | 220975 | 121 | 0.07390 | 0.00062 | 1.61684 | 0.15782 | 0.15867 | 0.01543 | 1039 | 8 | 949 | 85 | 9 |
| 58 | 26797 | 133 | 0.06836 | 0.00122 | 1.33880 | 0.14747 | 0.14204 | 0.01544 | 879 | 18 | 856 | 87 | 3 |
| 59 | 158565 | 151 | 0.07335 | 0.00062 | 1.61952 | 0.19075 | 0.16013 | 0.01881 | 1024 | 9 | 957 | 104 | 7 |
| 60 | 24454 | 132 | 0.06340 | 0.00124 | 1.08876 | 0.16273 | 0.12456 | 0.01846 | 722 | 21 | 757 | 105 | -5 |
| 61 | 91218 | 156 | 0.05471 | 0.00049 | 0.48359 | 0.03991 | 0.06411 | 0.00526 | 400 | 10 | 401 | 32 | 0 |
| 63 | 73558 | 173 | 0.05405 | 0.00057 | 0.46318 | 0.04888 | 0.06215 | 0.00653 | 373 | 12 | 389 | 39 | -4 |
| 64 | 60179 | 160 | 0.05446 | 0.00063 | 0.49787 | 0.04304 | 0.06631 | 0.00568 | 390 | 13 | 414 | 34 | -6 |
| 66 | 246227 | 171 | 0.11404 | 0.00094 | 4.55340 | 0.45195 | 0.28958 | 0.02864 | 1865 | 7 | 1639 | 142 | 14 |
| 67 | 103188 | 154 | 0.05499 | 0.00056 | 0.49278 | 0.04903 | 0.06500 | 0.00643 | 412 | 11 | 406 | 39 | 1 |
| 68 | 110448 | 155 | 0.10083 | 0.00092 | 3.38450 | 0.29116 | 0.24345 | 0.02083 | 1639 | 8 | 1405 | 107 | 16 |
| 69 | 96818 | 140 | 0.05528 | 0.00056 | 0.49430 | 0.04357 | 0.06485 | 0.00568 | 423 | 11 | 405 | 34 | 4 |
| 70 | 24690 | 97 | 0.06985 | 0.00117 | 1.47255 | 0.14062 | 0.15291 | 0.01438 | 924 | 17 | 917 | 80 | 1 |
| 71 | 101143 | 38 | 0.09030 | 0.00086 | 2.94223 | 0.17492 | 0.23632 | 0.01387 | 1432 | 9 | 1368 | 72 | 5 |
| 74 | 111356 | 18 | 0.06978 | 0.00081 | 1.54330 | 0.09570 | 0.16042 | 0.00977 | 922 | 12 | 959 | 54 | -4 |
| 79 | 104596 | 19 | 0.19411 | 0.00183 | 12.81392 | 0.80612 | 0.47878 | 0.02978 | 2777 | 8 | 2522 | 129 | 11 |
| 83 | 1546378 | 41 | 0.09616 | 0.00073 | 3.25336 | 0.19574 | 0.24537 | 0.01464 | 1551 | 7 | 1415 | 75 | 10 |
| 84 | 173320 | 26 | 0.10926 | 0.00102 | 4.47719 | 0.27776 | 0.29720 | 0.01823 | 1787 | 9 | 1677 | 90 | 7 |
| 86 | 109564 | 20 | 0.08286 | 0.00102 | 2.46738 | 0.15533 | 0.21597 | 0.01333 | 1266 | 12 | 1261 | 70 | 0 |
| 1 | 174650 | 65 | 0.05382 | 0.00058 | 0.45446 | 0.01360 | 0.06124 | 0.00171 | 364 | 24 | 383 | 10 | -5 |
| 3 | 82728 | 58 | 0.05592 | 0.00078 | 0.55309 | 0.02980 | 0.07174 | 0.00373 | 449 | 31 | 447 | 22 | 1 |
| 4 | 33195 | 50 | 0.06897 | 0.00101 | 1.44147 | 0.05628 | 0.15159 | 0.00548 | 898 | 30 | 910 | 31 | -1 |
| 5 | 185374 | 53 | 0.07251 | 0.00077 | 1.58698 | 0.05401 | 0.15873 | 0.00513 | 1000 | 22 | 950 | 28 | 5 |
| 6 | 67231 | 62 | 0.05567 | 0.00102 | 0.52728 | 0.02076 | 0.06870 | 0.00239 | 439 | 41 | 428 | 14 | 3 |
| 7 | 83622 | 62 | 0.05474 | 0.00063 | 0.51317 | 0.01823 | 0.06799 | 0.00229 | 402 | 26 | 424 | 14 | -6 |
| 8 | 170770 | 48 | 0.05604 | 0.00061 | 0.56466 | 0.01886 | 0.07307 | 0.00231 | 454 | 24 | 455 | 14 | 0 |
| 9 | 136843 | 40 | 0.05543 | 0.00061 | 0.52861 | 0.01926 | 0.06917 | 0.00240 | 429 | 24 | 431 | 14 | 0 |
| 10 | 113854 | 60 | 0.05516 | 0.00064 | 0.55167 | 0.01922 | 0.07254 | 0.00238 | 419 | 26 | 451 | 14 | -8 |
| 11 | 219035 | 38 | 0.05451 | 0.00056 | 0.48054 | 0.01475 | 0.06394 | 0.00185 | 392 | 23 | 400 | 11 | -2 |
| 12 | 50823 | 164 | 0.06021 | 0.00173 | 0.61341 | 0.03075 | 0.07390 | 0.00304 | 611 | 62 | 460 | 18 | 26 |
| 13 | 159336 | 45 | 0.05901 | 0.00064 | 0.72690 | 0.02480 | 0.08934 | 0.00289 | 567 | 24 | 552 | 17 | 3 |
| 14 | 48710 | 37 | 0.05787 | 0.00075 | 0.64017 | 0.02050 | 0.08024 | 0.00235 | 525 | 29 | 498 | 14 | 5 |
| 15 | 48770 | 23 | 0.05446 | 0.00067 | 0.50974 | 0.01656 | 0.06789 | 0.00204 | 390 | 28 | 423 | 12 | -9 |
| 16 | 110646 | 51 | 0.05562 | 0.00064 | 0.54231 | 0.01722 | 0.07071 | 0.00209 | 437 | 26 | 440 | 13 | -1 |
| 17 | 28091 | 45 | 0.05420 | 0.00085 | 0.53464 | 0.01693 | 0.07155 | 0.00197 | 379 | 35 | 445 | 12 | -18 |
| 18 | 135897 | 44 | 0.05400 | 0.00061 | 0.46154 | 0.01376 | 0.06199 | 0.00171 | 371 | 26 | 388 | 10 | -5 |
| 19 | 416600 | 71 | 0.07252 | 0.00073 | 1.58240 | 0.05404 | 0.15825 | 0.00517 | 1001 | 20 | 947 | 29 | 6 |
| 20 | 79274 | 56 | 0.05640 | 0.00079 | 0.54315 | 0.01854 | 0.06985 | 0.00217 | 468 | 31 | 435 | 13 | 7 |
| 22 | 35528 | 76 | 0.06183 | 0.00194 | 0.77637 | 0.03468 | 0.09107 | 0.00290 | 668 | 67 | 562 | 17 | 17 |
| 23 | 195379 | 102 | 0.05546 | 0.00068 | 0.48225 | 0.01491 | 0.06306 | 0.00179 | 431 | 27 | 394 | 11 | 9 |
| 24 | 155106 | 56 | 0.07418 | 0.00076 | 1.70847 | 0.05378 | 0.16703 | 0.00497 | 1046 | 21 | 996 | 27 | 5 |
| 25 | 37730 | 65 | 0.07359 | 0.00096 | 1.67888 | 0.05596 | 0.16546 | 0.00507 | 1030 | 26 | 987 | 28 | 5 |
| 26 | 105935 | 69 | 0.05445 | 0.00059 | 0.47773 | 0.01629 | 0.06363 | 0.00206 | 390 | 24 | 398 | 12 | -2 |
| 28 | 56068 | 68 | 0.05438 | 0.00068 | 0.48350 | 0.01840 | 0.06449 | 0.00232 | 387 | 28 | 403 | 14 | -4 |
| 29 | 101814 | 79 | 0.07383 | 0.00083 | 1.69167 | 0.05660 | 0.16617 | 0.00524 | 1037 | 23 | 991 | 29 | 5 |
| 30 | 246354 | 84 | 0.11108 | 0.00113 | 4.64211 | 0.19107 | 0.30309 | 0.01209 | 1817 | 18 | 1707 | 60 | 7 |
| 31 | 83943 | 77 | 0.05500 | 0.00065 | 0.50616 | 0.01619 | 0.06675 | 0.00198 | 412 | 27 | 417 | 12 | -1 |

Appendix 2

*Supplementary Data*

http://earth.geology.yale.edu/~ajs/SupplementaryData/2014/07DeSouza.xlsx

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