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SHORT PAPER

Evidence for Silurian sinistral accretion of Avalon composite terrane in Canada

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The Kingston dyke complex forms a regionally developed belt of sheeted bimodal dykes within the Avalon composite terrane of southern New Brunswick, Canada. Dyke orientation relative to the belt suggests their injection accompanied sinistral movement, and the belt has previously been attributed to transform activity within the late Precambrian magmatic arc regime typical of the Avalon composite terrane in the Northern Appalachians. However, rhyolite dykes of the sheeted complex yield a U-Pb age of 435.5 ± 1.5 Ma that is interpreted to date their emplacement. The complex therefore provides evidence of Early Silurian sinistral displacement in the Northern Appalachians. Such movement is suggested by palaeomagnetic data and may record the accretion of the Avalon composite terrane to cratonic North America.

Siluro–Devonian rocks in the Avalon composite terrane of the Northern Appalachians outcrop in a discontinuous zone termed the Coastal Volcanic belt (Bradley 1983 and references therein) which extends from southern Maine and New Brunswick to northern Nova Scotia (Fig. 1a). These rocks consist mainly of low grade bimodal volcanic rocks overlain by fossiliferous siliciclastic rocks. They occupy an important position in the stratigraphic record between the Taconian structural telescoping of the North American continental margin of Iapetus, which took place prior to the accretion of parts of the Avalon composite terrane to North America, and the widespread Devono–Carboniferous magmatism that is considered to post-date this event (Keppie 1989). The tectonic setting of these igneous rocks is therefore relevant to the relationship between the Avalon composite terrane and cratonic North America during Silurian times. However, the tectonic significance of the Coastal Volcanic belt remains controversial. Bradley (1983) attributed the belt to the development of a volcanic arc along the outboard margin of a Silurian ocean (recorded in the Fredericton and Merrimack troughs) prior to its Early Devonian (Acadian) closure. An opposing volcanic arc along the inboard margin of this ocean was considered to be represented by the Piscataquis–Tobique volcanic belts of north-central Maine, northern New Brunswick and the Gaspé Peninsula. However, available geochemical data suggest that volcanic rocks of the Coastal Volcanic belt, the mafic members of which are predominantly continental tholeiites, formed in local intracontinental extensional environments (e.g. Murphy 1987) and a similar setting has recently been proposed for the Piscataquis–Tobique belts (Dostal *et al.* 1989 and references therein).

Within the Coastal Volcanic belt of southern New Brunswick, the bimodal Kingston dyke complex forms a major tectonic feature that occupies a NE-trending fault-bounded zone in the Avalon composite terrane (Fig. 1b). The bulk of the complex has generally been assigned a late Precambrian emplacement age on the basis of field relations (Rast 1979; Rast & Dickson 1982; Currie 1987) and its emplacement has been interpreted to have accompanied significant sinistral movement (Currie 1988*a*). Hence, the complex has played an important role in the development of late Precambrian tectonic models for the Avalon composite terrane of southern New Brunswick (Nance 1987; Currie 1988*b*). The age data presented here, however, suggest an earliest Silurian emplacement age for the bulk of the complex and, for the first time, provide age-constrained kinematic evidence in support of the Early Silurian sinistral displacement of the Avalon composite terrane relative to cratonic North America suggested by palaeomagnetic data (Briden *et al.* 1988). Late Precambrian models of sinistral transtension may therefore need to be re-evaluated.

Geological setting. The Kingston dyke complex takes the form of a mafic to bimodal dyke swarm that defines a linear zone up to 10 km across strike and more than 125 km in length (Fig. 1b). Mafic dykes in an inlier of deformed Precambrian granitoid bodies near Moncton, New Brunswick, may extend the dyke swarm a further 100 km northeast (Rast & Dickson 1982). The complex is bordered on both sides by major mylonite zones that contain kinematic indicators of dextral shear sense (Leger & Williams 1986) and have been reactivated as brittle faults. These structures include the Pocologan mylonite zone and brittle Kennebecasis fault to the southeast (Rast & Dickson 1982) and the Seven Mile Lake mylonite zone and Belleisle fault to the northwest (Currie 1988*a*). Outlying dykes and inclusions within the complex suggest that it originally intruded units of the Proterozoic Green Head Group and calc-alkaline granitoid bodies and associated volcanic rocks of the late Precambrian Avalonian succession.

The southwestern part of the complex (the Beaver Harbour dyke swarm) has been described in detail by Rast (1979), Rast & Dickson (1982) and Currie (1987, 1988*a*). These authors recognized at least two generations of dykes that trend broadly NE–SW, are predominantly mafic, and make up 40% to 80% of the outcrop. Currie (1988*a*), however, describes both felsic and mafic phases, the former having occasional flow banding and glomeroporphyritic textures. All dykes are variably metamorphosed in the greenschist and, locally, the epidote amphibolite facies. However, the earlier dykes are strongly deformed, schistose, non-porphyritic amphibolites whereas the later dykes are noticably less deformed and are porphyritic metadiabases with partly recrystallized plagioclase phenocrysts and well-preserved ophitic textures. Rast & Dickson (1982) further subdivide the dykes into tholeiitic amphibolites and xenolith-bearing, alkalic lamprophyres that predate the main dyke swarm, and essentially undeformed basic intrusions or probable Siluro-Devonian age that post-date it. Mafic members of the swarm are mainly rift-related continental tholeiites (Dickson 1985), and the swarm itself is generally interpreted to be broadly coeval with presumed late Precambrian mylonitization along the Pocologan mylonite zone.

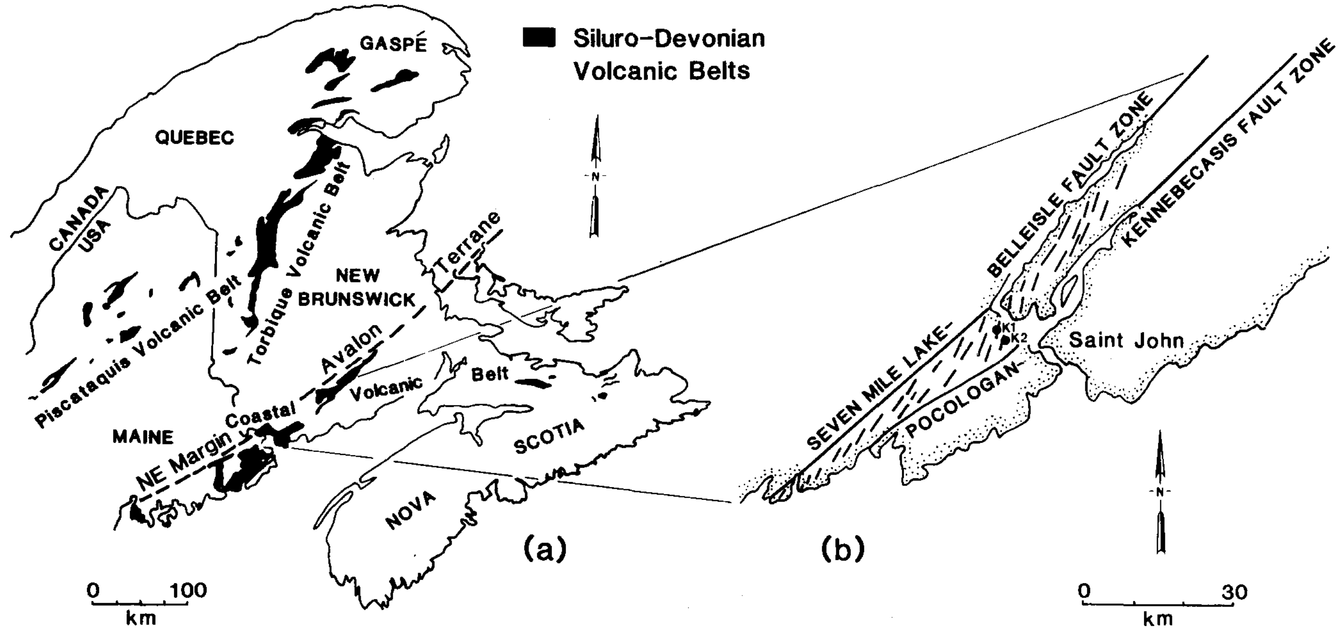

Fig. 1. (**a**) Distribution of Siluro–Devonian volcanic rocks in the northern part of the mainland Appalachians (modified after Dostal *et al.* 1989). (**b**) Sketch map of southern New Brunswick showing schematic dyke trends within the Kingston complex and the traces of the Seven Mile Lake–Belleisle and Pocologan–Kennebecasis fault zones that respectively bound the complex to the northwest and southeast (modified after Leger & Williams 1988).

In the northeastern portion of the complex described by Currie (1986), the dykes locally trend north–south are commonly sheeted and are distinctly bimodal. The felsic and mafic dykes typically range from 50 cm to 50 m in thickness, have both mutally chilled and mutually cross-cutting contacts consistent with their broadly coeval emplacement, and alternate in an essentially regular fashion between tholeiitic diabase and rhyolitic–dacitic compositions. The felsic dykes vary from aphanitic grey rhyolite with pink feldspar phenocrysts, through red or grey felsite, to microgranite, whereas the mafic dykes are massive, fine-grained amphibolite, porphyritic hornblende–plagioclase rocks and minor chloritized diabase. Some of the dykes have a weak cleavage parallel to the dyke margins but most are massive. This strongly bimodal portion of the complex is spectacularly exposed on the section of Route 7 north of Saint John that was sampled in this study.

In the absence of definitive radiometric data, the age of the Kingston complex has remained uncertain. A K-Ar actinolite age of 369 ± 21 Ma was reported by Helmstaedt (1968) from a mafic dyke within the complex. However, dyke emplacement and the development of the Pocologan mylonite zone have long been considered to be broadly contemporaneous late Precambrian events on the basis of field arguments (e.g. Nance 1988). Chief among these is the apparent restriction of both dykes and ductile shear zones to units of the late Precambrian succession and their absence in demonstrably Lower Palaeozoic rocks.

However, contemporaneous mylonitization and dyke emplacement is inconsistent with available kinematic data. Sense of shear criteria in the form of asymmetric augen, S-C and C-C′ structures indicate a dextral sense of ductile shear along the Pocologan mylonite zone (Leger & Williams 1986). Given the NE–SW orientation of this zone (Fig. 1b) and hence a broadly north–south extension direction during dextral shear, the expected initial orientation of coeval dykes would be east–west (Leger & Williams 1988). East–west dykes have not been encountered within the complex. Instead, the dykes trend between NE–SW and north–south. Hence, their orientation is commonly oblique to the faulted margins of the Kingston complex in a fashion that suggests their emplacement accompanied significant sinistral movement (Currie 1988*a*; Nance 1988). This assumes that the bounding faults approximately define the original margins of the complex and that the entire region between them has not undergone clockwise rotation in excess of 90°. Although neither can be demonstrated with certainty, these assumptions are supported by the absence of sheeted dykes beyond the bounding faults, by the present sigmoidal distribution of dykes within the complex (Fig. 1b), and by the absence of folded dykes and a prominent flattening fabric that would be an expected consequence of their clockwise rotation. In addition, a Kingston complex amphibolite dyke sampled within the Pocologan mylonite zone has recently yielded an ^{40}Ar/^{39}Ar hornblende age of 411 ± 2 Ma that is interpreted to date the most recent (dextral) phase of ductile shear (Dallmeyer & Nance 1989). Hence, even an overlapping relationship in space and time with the Pocologan mylonite zone no longer implies a pre-Palaeozoic age for the Kingston dyke complex. Our age data, together with that of Dallymeyer & Nance (1989), indicate a Silurian age for the predominantly massive, main phase of the Kingston complex. Thus the bimodal sheeted complex is significantly younger than the earlier, strongly deformed dykes for which a late Precambrian age remains possible.

Analytical methods and results. Zircon was processed by a method similar to that of Krogh (1973), using a mixed ^{205}Pb-^{233}U-^{235}U spike. Samples were run on a VG-Sector

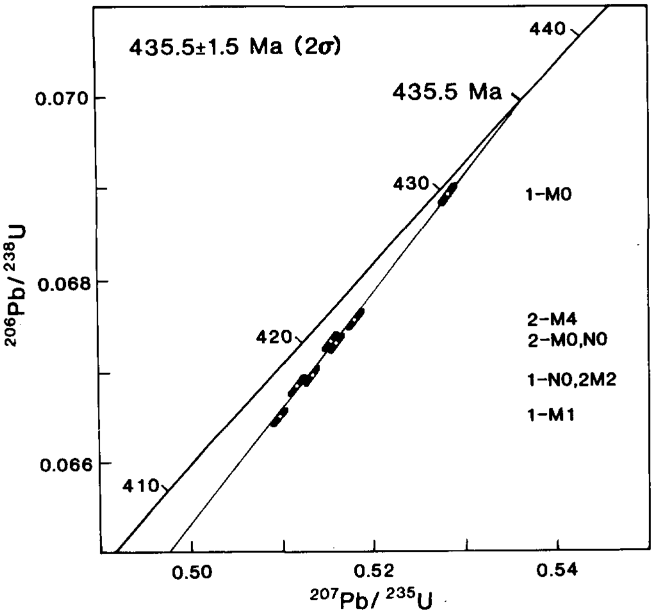

Fig. 2. U-Pb concordia diagram for zircons from rhyolite dykes of the Kingston complex sampled on Route 7 between Grand Bay and Westfield, New Brunswick.

mass spectrometer, and U was measured as the dioxide on the same filament as the Pb. The blank for the entire procedure ranges from 7 to 30 pg Pb. Dimensions of the data symbols shown in Fig. 2 are at the 95% confidence level and include measurement error, confidence in the fractionation factors, error in the U/Pb ratio of the spike, and the effect of the common Pb correction. Table 1 lists the isotopic data.

The rock samples are from fresh outcrops of rhyolite dykes exposed in new road cuts on Route 7 northeast of Saint John, New Brunswick, that provide a spectacular cross-section of the Kingston complex between Grand Bay and Westfield. Of four samples collected across the section, two yielded zircons. These are from 1–2 m dykes on the west side of the highway, 850 m north of Milligan Brook (sample K1), and on the east side of the highway, 300 m south of Milligan Brook (sample K2). There is only one population of zircons and these are clear, colourless, euhedral crystals averaging 60 μm long and 40 μm wide.

Samples of various magnetic fractions give similar ^{207}Pb/^{206}Pb ages, ranging from 433–437 Ma (Table 1), and the two dykes give the same age. There is insufficient spread (Fig. 2) to define a lower intercept well, but the points lie within error of a discordia from zero to 435.5 Ma. The fractions are only 1.5 to 4% discordant, so that the average ^{207}Pb/^{206}Pb age of 435.5 ± 1.5 (2σ) Ma is considered to be a reliable and precise age for the emplacement of the dykes sampled.

Interpretation. Although we cannot preclude the possibility of late Precambrian dykes within the Kingston complex, the zircon age of *c.* 435 Ma reported here is considered to date the emplacement of the sampled rhyolite dykes and, hence, the main bimodal component of the swarm. This is consistent with the single, homogeneous zircon population contained in both samples; the clear, euhedral shape of the zircon crystals; and the lack of a significant positive lower intercept on the concordia diagram which precludes loss of lead through metamorphism. An earliest Silurian crystallization age clearly conflicts with most current interpretations that consider the emplacement of the main portion of the complex and the development of its bordering mylonite zones to be closely related late Precambrian events. Instead, the development of the dextral shear zones that affect the margins of the complex must be of Silurian or younger age as proposed by Leger & Williams (1986) and supported by the ^{40}Ar/^{39}Ar hornblende age of 411 ± 2 Ma obtained by Dallmeyer & Nance (1989) from a mafic dyke within the Pocologan mylonite zone. However, a *c.* 435 Ma emplacement age for the dyke complex equally demonstates pre-Silurian ductile shear along those mylonite zones that are cross-cut by undeformed Kingston dykes (Rast & Dickson 1982; Currie 1988*b*). Hence, the Pocologan and, presumably, the Seven Mile Lake mylonite zones are likely to have experienced histories of repeated ductile shear, only the latest of which is recorded in their present dextral fabrics.

A *c.* 435 Ma emplacement age removes the Kingston complex from the late Precambrian Avalonian succession and places it within the bimodal, Siluro-Devonian Coastal Volcanic belt (Fig. 1a) of the Northern Appalachians (Bradley 1983). As a result, the oblique orientation of the complex relative to the trend of its component dykes (Fig. 1b) can no longer be used as evidence for late Precambrian sinistral movement in the Avalon composite terrane of

Table 1. *U-Pb data*

Zircon* fraction	Weight (mg)	U (ppm)	Pb_{rad} (ppm)	^{206}Pb†/^{204}Pb	^{208}Pb‡/^{206}Pb	^{206}Pb‡/^{238}U	^{207}Pb‡/^{235}U	^{207}Pb‡/^{206}Pb	^{207}Pb/^{206}Pb age (Ma)
K1-N0	0.106	1331	108.6	1585	0.3623	0.06684	0.5118	0.05553	433.7
-M0	0.074	700	56.4	706	0.3029	0.06891	0.5282	0.05559	436.2
-M1	0.372	1362	110.9	3468	0.3663	0.06650	0.5098	0.05560	436.5
K2-N0	0.125	298	23.4	2492	0.2977	0.06734	0.5162	0.05589	436.0
-M0	0.131	337	26.6	2573	0.3031	0.06734	0.5154	0.05552	433.0
-M2	0.128	359	32.3	1756	0.5051	0.06693	0.5129	0.05558	435.8
-M4	0.100	378	29.9	2308	0.3041	0.06754	0.5179	0.05562	437.0

* N0/M0 are non-magnetic/magnetic fractions and numerals 0, 1, etc. are degrees tilt on a Frantz separator. All fractions consist of zircon grains of average size 40 × 60 μm.

† Atomic ratios corrected for fractionation and spike.

‡ Atomic ratios corrected for fractionation, spike, blanks, and common Pb from the model of Stacey & Kramers (1975).

southern New Brunswick although movement of this sense and age is widespread within the Avalonian–Cadomian belt (Murphy & Nance 1989). Instead, the kinematic significance of the dyke complex now bears on the tectonics of the Silurian Coastal Volcanic belt, and therefore supports a sinistral shear setting for this volcanic regime (Dostal *et al.* 1989). In addition, the complex now provides supportive evidence for Early Silurian sinistral movement between the Avalon composite terrane and cratonic North America (Currie & Piasecki 1989). This sense of movement is suggested by palaeomagnetic data and has been used as evidence for progressive sinistral convergence in the southeastern part of the Iapetus ocean during the accretion of the Avalon composite terrane (Keppie 1989).

Discussion. Bimodal magmatism of Siluro–Devonian age is widespread within the Avalon composite terrane and commonly occurs adjacent to major transcurrent faults (Murphy 1987). The magmatic affinity of the mafic rocks in all areas is tholeiitic and the volcanic rocks are now thought to have been emplaced in an intracontinental extensional and/or strike-slip environment (Dostal *et al.* 1989 and references therein). Yet, in the absence of kinematic data, it has not been possible to evaluate whether the tectonic setting and magmatic affinity of these rocks are regionally or locally controlled (Murphy 1987). The orientation of dykes within the Kingston complex, however, supports *regional* sinistral shear during dyke emplacement.

A regional strike-slip regime of this shear sense may be of fundamental importance to the nature of the accretion of the Avalon composite terrane to cratonic North America. On the basis of palaeomagnetic data and structures associated with obduction, Keppie (1989) has suggested that progressive, sinistrally oblique convergence in the southeastern part of Iapetus, beneath the mid-to-late Ordovician Bronson Hill–Miramichi–La Poile volcanic arc complex, occurred throughout Ordovician and Silurian times, leading to the closure of Iapetus and the sinistral emplacement of the Avalon composite terrane along the vertical, deep-crustal Dover–Turtle Head fault system. Palaeomagnetic data for the Silurian (Briden *et al.* 1988) suggest that the Avalon composite terrane was moving sinistrally with respect to cratonic North America during this interval and reached its present relative palaeolatitude during initial accretion of the outboard Meguma terrane in the earliest Devonian (Keppie & Dallmeyer 1987). Keppie (1989) attributes the latter convergence, which is broadly coincident with the development of dextral shear zones in southern New Brunswick at *c.* 410 Ma (Dallmeyer & Nance 1989), to the dextral closure of the Theic ocean between the Avalon composite terrane and Gondwanaland. Hence, an earliest Silurian emplacement age for the bimodal portion of the Kingston dyke complex provides, for the first time, age-constrained kinematic data for a critical period in the accretionary history of the Avalon composite terrane.

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References

BRADLEY, D. C. 1983. Tectonics of the Acadian orogeny in New England and adjacent Canada. *Journal of Geology*, **91**, 381–400.

BRIDEN, J. C., KENT, D. B., LAPOINT, P. L., LIVERMORE, R. A., ROY, J. L., SEGUIN, M. K., SMITH, A. G., VAN DER VOO, R., & WATTS, D. R. 1988. Palaeomagnetic constraints on the evolution of the Caledonian–Appalachian orogen. *In*: HARRIS, A. L. & FETTES, D. C. (eds) *The Caledonian–Appalachian orogen*. Geological Society, London, Special Publication, **38**, 35–48.

CURRIE, K. L. 1986. The stratigraphy and structure of the Avalonian terrane around Saint John, New Brunswick. *Maritime Sediments and Atlantic Geology*, **22**, 278–295.

—— 1987. Late Precambrian igneous activity and its tectonic implications, Musquash-Loch Alva region, southern New Brunswick. *In*: *Current research, part A*, Geological Survey of Canada, Paper **87-1A**, 663–671.

—— 1988*a*. Saint George map area: the end of the Avalon zone in southern New Brunswick. *In*: *Current research, part B*, Geological Survey of Canada, Paper **88-1B**, 9–16.

—— 1988*b*. The western end of the Avalon zone in southern New Brunswick. *Maritime Sediments and Atlantic Geology*, **24**, 339–352.

—— & PIASECKI, M. A. J. 1989. Kinematic model for southwestern Newfoundland based upon Silurian sinistral shearing. *Geology*, **17**, 938–941.

DALLMEYER, R. D. & NANCE, R. D. 1989. ^{40}Ar/^{39}Ar mineral age record of polyphase tectonothermal activity in the Avalon terrane of southern New Brunswick. *Geological Association of Canada, Program with Abstracts*, **14**, A126.

DICKSON, W. L. 1985. *Geology, geochemistry and petrology of the Precambrian and Carboniferous rocks between Saint John and Beaver Harbour, southern New Brunswick.* PhD thesis, University of New Brunswick.

DOSTAL, J., WILSON, R. A., & KEPPIE, J. D. 1989. Geochemistry of Siluro–Devonian volcanic rocks in northern and central New Brunswick (Canada): Tectonic implications. *Canadian Journal of Earth Sciences*, **26**, 1282–1296.

HELMSTAEDT, H. 1968. *Structural analysis of the Beaver Harbour area, Charlotte County, New Brunswick.* PhD thesis, University of New Brunswick.

KEPPIE, J. D. 1989. Northern Appalachian terranes and their accretionary history. *In*: DALLMEYER, R. D. (ed.) *Terranes in the circum-Atlantic Paleozoic orogens*. Geologocial Society of America, Special Paper **20**, 159–192.

—— & DALLMEYER, R. D. 1987. Dating transcurrent terrane accretion; An example from the Meguma and Avalon Composite terranes in the northern Appalachians. *Tectonics*, **6**, 831–847.

KROGH, T. E. 1973. A low contamination method for hydrothermal decompostion of zircon and extraction of U and Pb for isotopic age determinations. *Geochimica et Cosmochimica Acta*, **37**, 485–494.

LEGER, A. & WILLIAMS, P. F. 1986. Transcurrent faulting history of southern New Brunswick. *In*: *Current research, part B*, Geological Survey of Canada, Paper **86-1B**, 111–120.

—— & —— 1988. Comment on "Model for the Precambrian evolution of the Avalon terrane, southern New Brunswick, Canada". *Geology*, **16**, 475–476.

MURPHY, J. B. 1987. Petrology of Upper Ordovician-Lower Silurian rocks of the Antigonish Highlands. *Canadian Journal of Earth Sciences*, **24**, 752–759.

—— & NANCE, R. D. 1989. Model for the evolution of the Avalonian–Cadomian belt. *Geology*, **17**, 735–738.

NANCE, R. D. 1987. Model for the Precambrian evolution of the Avalon terrane in southern New Brunswick, Canada. *Geology*, **15**, 753–756.

—— 1988. Reply to Comment on "Model for the Precambrian evolution of the Avalon terrane, southern New Brunswick, Canada". *Geology*, **16**, 476.

RAST, N. 1979. Precambrian meta-diabases of southern New Brunswick—the opening of the Iapetus Ocean? *Tectonophysics*, **59**, 127–137.

—— & DICKSON, W. L. 1982. The Pocologan mylonite zone. *In*: ST-JULIEN, P. & BELAND, J. (eds) *Major structural zones and faults of the northern Appalachians*. Geological Association of Canada, Special Paper **24**, 249–261.

STACEY, J. S. & KRAMERS, J. D. 1975. Approximation of terrestrial lead istope evolution by a two-stage model. *Earth and Planetary Science Letters*, **26**, 207–221.

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