Introduction

Yvette D. Kuiper
Department of Geology and Geological Engineering, Colorado School of Mines, Golden, Colorado 80401, USA

J. Brendan Murphy
Department of Earth Sciences, St. Francis Xavier University, 5009 Chapel Square, Antigonish, Nova Scotia, B2G 2W5, Canada

R. Damian Nance
Department of Geological Sciences, Ohio University, Athens, Ohio 45701, USA

Robin A. Strachan
School of the Environment, Geography and Geosciences, University of Portsmouth, Portsmouth, PO1 3QL, UK

Margaret D. Thompson
Department of Geosciences, Wellesley College, 106 Central Street, Wellesley, Massachusetts 02481, USA

This Special Paper covering "New Developments in the Appalachian-Caledonian-Variscan Orogen" follows our 2019 GSA Annual Meeting session with the same title (convened by Kuiper, Nance, Murphy, and Strachan; 32 contributions) and our 2019 GSA Northeastern (NEGSA) Section meeting session "Peri-Gondwanan Terranes and Their Origins: What Do We Really Know?" (convened by Kuiper, Thompson, and Nance; 14 contributions). It has been a quarter century since the publication of the GSA Special Paper, *Avalonian and Related Peri-Gondwanan Terranes of the Circum-North Atlantic*, by Nance and Thompson (1996). With new analytical and field techniques, and increased international communication and collaboration, much more has been learned about the Appalachian-Caledonian-Variscan orogen. Cross-Atlantic correlations are better understood, and the database that helps us understand the origins of Gondwanan terranes continues to grow. This trove of new information is what sparked our NEGSA session. In our GSA Annual Meeting session, geoscientists who work in North America, Europe, and northwest Africa presented and discussed various aspects of the Appalachian-Caledonian-Variscan orogen. This Special Paper stems from these two sessions and offers additional chapters, and gives a comprehensive overview of our current understanding of the evolution of this orogen.

This volume takes the reader on a clockwise path around the North Atlantic Ocean: starting in the U.S. and Canadian Appalachians; then along the Caledonides of Spitsbergen, Scandinavia, Scotland, and Ireland; and ending in the Variscides of Morocco. The volume begins with two general overview papers. Kroner et al. (Chapter 1) discuss relative plate motions and Paleozoic orogenies during the formation of western Pangea. They combine the plate kinematic model of the Pannotia-Pangea supercontinent cycle with geological constraints for the various Paleozoic orogens. A key result from their model is that both initial breakup of Pannotia and assembly of western Pangea were facilitated by subduction and seafloor spreading at the leading and trailing edges of the North American plate and Gondwana, respectively. They conclude that slab pull is a sufficient driving force to explain the entire Pannotia–western Pangea supercontinent cycle. *Romer and Kroner* (Chapter 2) then discuss how provenance controls the distribution of endogenic Sn-W, Au, and U mineralization within the Gondwana-Laurussia plate-boundary zone. The mineral deposits are the result of the superposition of a series of exogenic and endogenic processes, where endogenic processes are controlled by orogenic episodes during the assembly of western Pangea, and exogenic processes are linked to the formation of suitable source rocks for later mineralization. Hence, the distribution of magmatic and hydrothermal Sn-W-Ta, Au, and U deposits is controlled by the distribution of fertile protoliths and by remobilization as a result of the Acadian and Variscan/Alleghanian orogenies.

Three papers address various aspects of the southeastern New England Avalon terrane. *Thompson et al.* (Chapter 3) present Lu-Hf analyses from Ediacaran granitoids and related volcanic rocks formed during the main phase of arc-related magmatism. Granites in a belt north and west of the Boston Basin are more evolved than upfaulted granites and slightly younger

Kuiper, Y.D., Murphy, J.B., Nance, R.D., Strachan, R.A., and Thompson, M.D., 2022, Introduction, *in* Kuiper, Y.D., Murphy, J.B., Nance, R.D., Strachan, R.A., and Thompson, M.D., eds., New Developments in the Appalachian-Caledonian-Variscan Orogen: Geological Society of America Special Paper 554, p. v–vii, https://doi.org/10.1130/2022.2554(001).

volcanic units in the south, which are more juvenile. Isotopic compositions and high-precision U-Pb geochronological constraints for southeastern New England are more consistent with those of the Cobequid and Antigonish Highlands, mainland Nova Scotia, and New Brunswick's Caledonia terrane than those of the Mira terrane of Cape Breton Island or the Avalon terrane of Newfoundland. The authors propose that this relationship provides a starting point for a model in which episodic West Avalonian arc magmatism began along the Tonian margin of Baltica and terminated during diachronous late Ediacaran arc-arc collision with the Ganderian margin of Gondwana. *Severson et al.* (Chapter 4) present new detrital zircon U-Pb ages and Lu-Hf isotopic data from metasedimentary units along the western boundary of the composite southeastern New England Avalon terrane and compare them with existing data from Avalonia in New England and Canada. The results suggest that both regions were derived from the same cratonic sources. The εHf values of all compiled Avalonian samples overlap with both Amazonia and Baltica, suggesting that there is a mixed signature between cratonic sources, possibly as a result of previous collision and transfer of basement fragments between these cratons during the formation of supercontinent Rodinia, or during subsequent arc collisions. *Kuiper et al.* (Chapter 5) conducted U-Pb detrital zircon analysis of sedimentary rocks from multiple previously interpreted subterranes of the southeastern New England Avalon terrane. Rocks from the Neoproterozoic Newport Group in southern Rhode Island yielded a detrital zircon age signature that is significantly different from other samples in the terrane and are most consistent with a northwest African affinity. The Newport Group may thus represent a subterrane, terrane, or other crustal block with a different origin and history from the southeastern New England Avalon terrane to the northwest.

In the northern Appalachians of Canada, *Dostal et al.* (Chapter 6) discuss geochemical and Nd isotopic constraints on the origin of uppermost Silurian rhyolitic rocks in northern New Brunswick. Voluminous Ganderian bimodal volcanic rocks are subaerial units that were deposited in an extensional setting, with mafic parts representing continental tholeiites. Felsic rocks are rhyolites with calc-alkaline affinities. Geochemical data indicate that the felsic melts were likely sourced from heterogeneous, Neoproterozoic lower crust, and generated by dehydration melting triggered by heat derived from underplated mafic magma. The Nd isotopic data suggest that the lower crust of Ganderia is similar to that of Avalonia in northern mainland Nova Scotia, and that the two microcontinents share a common Neoproterozoic history and origin as continental blocks rifted from neighboring parts of Gondwana. *White et al.* (Chapter 7) present U-Pb zircon ages and Sm-Nd isotopic data from the Cobequid Highlands of Nova Scotia. Contrasts in ages and rock types resulted in the identification of fault-bounded blocks of Neoproterozoic assemblages. These include the Mount Ephraim block, which displays Neoproterozoic pre–752 Ma, high-grade regional metamorphism and deformation and 752–730 Ma subduction-related magmatism, previously unrecognized in Avalonia. *Pollock et al.* (Chapter 8) conducted Lu-Hf analyses on zircon from Neoproterozoic magmatic arc sequences to investigate the crustal evolution of Avalonia and Ganderia in the northern Appalachians between Maine, USA, and Newfoundland, Canada. Avalonian zircon typically yields negative initial εHf values and 1.2 to 0.8 Ga Hf-T_{DM} (depleted mantle) model ages, whereas Ganderian zircon typically shows positive initial εHf values and 1.8 to 1.0 Ga Hf-T_{DM} model ages. Cryogenian–Ediacaran magmatism is interpreted to have resulted from reworking of an evolved Mesoproterozoic crustal component during long-lived, subduction-dominated accretionary processes along the northern margin of Amazonia. A change in Hf isotope trajectory during the Ediacaran reflects a greater contribution of isotopically evolved material consistent with arc-arc style collision of Ganderia with Avalonia. The shallowly sloping Hf isotopic pattern for Paleozoic Ganderian magmatism remains continuous for ~200 m.y., consistent with tectonic models of subduction in the Iapetus and Rheic oceans and episodic accretion of juvenile crustal terranes to Laurentia.

In Newfoundland, Canada, *Willner et al.* (Chapter 9) discuss conditions and timing of metamorphism near the Baie Verte Line, a suture zone of an arc-continent collision along the Laurentian margin that was repeatedly re-activated during the Late Ordovician Taconic 3, Silurian Salinic and Early–Late Devonian Acadian/Neoacadian orogenic cycles. *Hodgin et al.* (Chapter 10) interpret the tectonic history of the Dashwoods terrane of western Newfoundland on the basis of U-Pb geochronology. Using results from detrital zircon from sedimentary rocks and inherited zircon from igneous rocks, they challenge the correlation of the Dashwoods terrane with Laurentia and suggest instead a plate-tectonic model in which the Taconic orogeny was initiated by collision of Gondwanan arc terranes that closed the Iapetus Ocean along the Baie Verte–Brompton Line.

Maher et al. (Chapter 11) provide a detailed structural and petrographic description of core complex fault rocks of the Silurian to Devonian Keisarhjelmen Detachment in NW Spitsbergen. They conclude that the kinematics, retrogression, and ductile-brittle transition are consistent with development of a core complex formed by orogen-parallel extension associated with transtension during the late Silurian and Early to Middle Devonian. The authors discuss potential relationship with coeval plate-scale strike-slip faults in Svalbard and Norwegian core complexes and Devonian basins. *Baird et al.* (Chapter 12) determine the pressure-temperature-deformation-time path for the Seve Nappe Complex of the Kebnekaise Massif in the Arctic Sweden Caledonides. The tectonic history for these rocks includes subduction and exhumation during a Cambrian–Ordovician pre-Scandian event, followed by thrusting of the Seve Nappe Complex and neighboring rocks onto Baltica during the Silurian Scandian orogeny. *Hollocher et al.* (Chapter 13) investigated metamorphosed igneous rocks of the Blåhø Nappe of the central Norwegian Scandinavian Caledonides. They conclude that the protoliths of these rocks formed in an oceanic arc–back-arc setting that is different from protoliths in the Seve Nappe Complex. *Jakob et al.* (Chapter 14) have revised the tectono-stratigraphic scheme for the Scandinavian Caledonides and discuss implications of these revisions for the understanding of the Scandian orogeny. Baltica-derived tectonic units collided with the Iapetan/Laurentian subduction complexes as early as ca. 450 Ma. The initial collision was followed by continuous in-sequence nappe formation of Baltica-derived units, which occurred penecontemporaneously with the opening of a marginal basin in the upper plate. After the arrival of thick, buoyant Baltican crust at the trench, the main zone of convergence migrated outboard, the marginal basins closed, and its rock units were thrust out-of-sequence over the previously assembled nappe stack.

Archibald et al. (Chapter 15) give a comprehensive review of the age, lithogeochemical, and Nd-Sr isotopic compositions of some classic plutonic rocks emplaced in the Northern Highlands, Grampian, and Connemara terranes of the Caledonidian orogen of Scotland and Ireland. These Silurian–Devonian mafic and felsic-intermediate plutonic rocks were intruded during and after the late Caledonian Scandian orogeny. Felsic-intermediate magmas probably formed by fractionation from mafic magmas. Results are interpreted in terms of slab failure during the Scandian orogeny. On the basis of new U-Pb detrital zircon data, *Riggs et al.* (Chapter 16) investigate and discuss the sedimentary provenance of three Silurian basins in western Ireland that evolved during Iapetus closure. Their results, which suggest that local Dalradian rocks and contemporaneous volcanic centers are the sediment sources, are consistent with the interpretation that Ganderian continental fragments became part of Laurentia prior to the full closure of the Iapetus Ocean.

Finally, *Accotto et al.* (Chapter 17) conducted U-Pb detrital zircon geochronology on samples from the Ordovician metasedimentary rocks of the Moroccan Meseta in the northern Moroccan Variscides. Their data support previous interpretations that the Moroccan Meseta (and the entire northern Moroccan Variscides) formed part of the northern Gondwana passive margin.

ACKNOWLEDGMENTS

We are grateful to all authors and reviewers for their contributions, and all who attended our 2019 GSA Northeastern Section and Annual Meeting sessions. We thank Joan Florsheim (GSA Books Science Editor) and Jon Raessler (GSA Books Assistant) for their help, speedy responses, and endless patience, and April Leo (GSA Books Managing Editor) for final editing. This volume is a contribution to IGCP Project 683.

REFERENCE CITED

Nance, R.D., and Thompson, M.G., eds., Avalonian and Related Peri-Gondwanan Terranes of the Circum-North Atlantic: Geological Society of America Special Paper 304, https://doi.org/10.1130/SPE304, 380 p.