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Preface

Endings and beginnings: Paleogeography of the Neoproterozoic–Cambrian transition

1. Paleogeography at the "cutting edge"

The Neoproterozoic to Cambrian interval is of singular significance in Earth history, hosting a fundamental diversification of life and perhaps the most severe extremes in climate (Grotzinger et al., 1995; Kaufman et al., 1997). This transition featured widespread rifting and orogenic activity that accompanied the opening of new oceans and the closing of others during the Late Neoproterozoic–Early Paleozoic assembly of the supercontinent Gondwana (Trompette, 1997). The Neoproterozoic–Cambrian transition may also have had unusual geodynamic events such as rapid plate motions (Meert et al., 1993; McCausland and Hodych, 1998) and/or substantial "true polar wander," i.e. the bulk tumbling of the Earth's mantle and lithosphere with respect to its spin axis (Kirschvink et al., 1997; Evans, 2003). A newly introduced period in the global time scale, the Ediacaran, is delimited by the occurrence of the cap carbonate at its base which overlies the Marinoan global-scale glaciation (~630 Ma) and by the first occurrence of shelly fauna at the base of the Cambrian at 543 Ma, thus highlighting the transition from the Precambrian Earth to the more familiar Phanerozoic Earth (Knoll et al., 2004).

Knowledge of the paleogeography of the Neoproterozoic–Cambrian transition is fundamental to understanding the Late Neoproterozoic climate extremes, the rapidly evolving Ediacaran and Cambrian fauna, and global geodynamics. Paleogeography prior to the Middle Cambrian is poorly known, however, with few high quality (Van der Voo, 1993) paleomagnetic constraints and poor biogeographic control. A large part of the difficulty lies in the absence, prior to the Cambrian radiation, of useful index fossils for constraining depositional age and the possible spatial relationships and correlations between strata. Another, less-realized problem is the proliferation of peri-Laurentian and peri-Gondwanan terranes during Late Neoproterozoic to Cambrian time, obscuring the timing and nature of the geological linkages between continents (Cawood et al., 2001).

Most importantly, the formation of the supercontinent Gondwana by the end of the Neoproterozoic, and its persistence throughout Paleozoic time, has been a lynchpin for Pre-Pangea paleogeographic reconstructions. Gondwana contained much of the Earth's landmass during its existence, such that it has been possible with minimal information to estimate the global Paleozoic paleogeography and even plate boundary relationships with respect to the Gondwanan supercontinent (e.g., McElhinny et al., 2003; Stampfli and Borel, 2002). There is, however, great uncertainty as to the relative positions of the component cratons of Gondwana prior to its Cambrian final amalgamation. Furthermore, for the Neoproterozoic time prior to Gondwana's assembly there does not seem to have been a single, long-lived supercontinent with a defined paleogeography (Cordani et al., 2003; Murphy et al., 2004), despite concerted efforts to recognize and test proposed supercontinents such as Palaeopangea (Piper, 1976, 2000) and versions of Rodinia (Hoffman, 1991; Dalziel, 1997; Weil et al., 1998; Torsvik, 2003; Meert and Torsvik, 2003). Although the extent and configuration of Rodinia remains unresolved, the record of widespread "Grenville" age collisional 1.1–1.0 Ga orogenesis and circum-Laurentian Neoproterozoic rifting (cf. Hoffman, 1991) still suggests that a major, Laurentia-cored landmass existed during the Early Neoproterozoic (Meert and Torsvik, 2003).

As a result of the lack of supercontinental constraints, much more paleomagnetic and geological information will be required from each continent and continental fragment to develop robust global paleogeographies for Neoproterozoic through Cambrian time. The Neoproterozoic–Cambrian transition is, then, the "cutting edge" for resolving global paleogeography, where

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issues of regional tectonics, geodynamics, paleomagnetism, global change and biodiversity converge. Before this seminal interval, the Precambrian – nearly 88% of geologic time – is still poorly understood, and perhaps intractably so, without first solving the paleogeography of the Neoproterozoic–Cambrian transition.

2. Neoproterozoic–Cambrian global paleogeography

The papers of this special issue, "Endings and beginnings: Paleogeography of the Neoproterozoic–Cambrian transition," arise from a special session held at the Spring 2004 meeting of the American Geophysical Union in Montreal. These 12 contributions focus on several outstanding paleomagnetic and geological issues of the Precambrian–Cambrian transition paleogeography.

Paleomagnetic studies offer a unique, quantitative estimate of the paleolocations and motions of continents with respect to one another, provided that there are a sufficient number of successive, well determined paleomagnetic results for each continent. Tohver et al. (2006) provide a rigorous assessment of the currently known 1200–500 Ma paleomagnetic record for the tectonic elements of Africa and South America, drawn from published (and hitherto poorly accessible) paleomagnetic results. They find that, despite the sparseness of the paleomagnetic record, it is nevertheless possible to establish from latitudinal drift histories that: (1) West Gondwana cannot have been a complete entity until the Late Neoproterozoic–Cambrian collision of Amazonia-West Africa-Rio de la Plata with Congo-Sao Francisco-Kalahari; and (2) the latter, predominantly African core elements of Gondwana likely did not travel with Laurentia in Early Neoproterozoic time and therefore were not part of a Rodinia supercontinent. The paleomagnetic compilations of West Gondwana (Tohver et al., 2006), and for elements of East Gondwana (Powell and Pisarevsky, 2002; Meert, 2003), imply that Rodinia may at best have been an assemblage of continents, rather than a Pangea-like supercontinent occupying a single plate.

Rapalini (2006) further substantiates the Late Neoproterozoic–Cambrian timing of Gondwana assembly, reporting a new paleomagnetic result derived from sedimentary compaction-corrected red claystones of Ediacaran age in the Rio de la Plata craton. Comparison of this result with the handful of other coeval Gondwanan paleomagnetic results from Uruguay, eastern Africa, Arabia and Australia indicates that by Late Ediacaran time (ca. 550 Ma), Gondwana was already assembled or nearly so.

Laurentia is postulated to have been the core of the Rodinia supercontinent, largely based on lithostratigraphic evidence for the presence of mid-to-Late Neoproterozoic rift-drift successions along each of its margins (Hoffman, 1991). For each margin, the identity of the conjugate margin to Laurentia is controversial (Dalziel, 1997; Weil et al., 1998; Sears and Price, 2000; Wingate and Giddings, 2000; Cawood et al., 2001; Meert and Torsvik, 2003; Murphy et al., 2004). As a result, there is broad agreement on the existence of a Rodinia of some extent based on the widespread ca. 1.1 to 1.0 Ga collisional orogens, but there is no emerging consensus on its configuration.

Weil et al. (2006) refine the mid-Neoproterozoic paleomagnetic record for Laurentia, reporting an extensive study of the well-preserved ca. 800–750 Ma Uinta Mountains Group of northern Utah and Colorado. They confirm that Laurentia occupied a low-latitude position at ∼800 to 750 Ma, perhaps coinciding with the occurrence of worldwide glaciation, and that possible Rodinia cratonic relations along Laurentia's Cordilleran margin are no longer viable by the mid-Neoproterozoic, consistent with the widespread record of rift-to-drift activity along the margin during that time.

Gladkochub et al. (2006) update previous suggestions for a ca. 1 Ga Siberia-Arctic Canada connection with geochemical data and Ar-Ar, U-Pb geochronological results from three generations of mafic dykes and sills emplaced in the Neoproterozoic passive margin of southwestern Siberia. They note similarities in age and geochemistry of the older generation of sills with the plume-related ca. 723 Ma Franklin intrusions of northern Laurentia, and extend the ca. 1 Ga paleomagnetic-based fit of Siberia to Arctic Laurentia (Pisarevsky and Natapov, 2003) to the mid-Neoproterozoic. An implication of this mid-Neoproterozoic Siberia-Laurentia connection is that the Late Neoproterozoic passive margin along the Arctic flank of Laurentia may have bordered the Paleo-Asian Ocean, which probably contained an as yet unfathomed collage of Central Asian terranes, many of which accreted to Siberia and Baltica during its Paleozoic closure (e.g., Khain et al., 2003).

Rifting along Laurentia's eastern, Iapetan margin may have been complicated in latest Neoproterozoic–Cambrian time by the separation of terranes (Cawood et al., 2001). The rift-drift transition is recorded along the incipient Iapetan margin of Laurentia at the Precambrian–Cambrian boundary (Bond et al., 1984; Williams and Hiscott, 1987), but paleomagnetic evidence indicates that the oft-proposed conjugate margin Amazonia could not have been adjacent to eastern

Laurentia at 550 Ma (McCausland and Hodych, 1998). Either another craton was the conjugate margin to Laurentia, or Laurentia already faced an already open Iapetus Ocean at the time of the margin's rift-drift transition, with the ca. 550 Ma rifting marking the separation of one or several terranes (Cawood et al., 2001). Evidence for terrane separation includes the Argentine Precordilleran terrane, which was derived from the Ouachita margin of Laurentia in the Early Cambrian. It traveled as an independent terrane in the mid-to-late Cambrian and was transferred to West Gondwana by mid-Paleozoic time (Thomas and Astini, 1996; Raplini and Astini, 1998). Other terranes, such as the Dashwoods block in western Newfoundland may have separated from Laurentia, only to have been re-accreted during the closure of the Iapetus Ocean (Waldron and van Staal, 2001).

Carter et al. (2006) present a case for the Laurentian origin of the Smith River Allochthon of the southern Appalachians, based on comparing its detrital zircon age and chemical record with that of the nearby preserved Laurentian margin. Although detrital zircons cannot be used to define a specific paleogeography, they can, when combined with other geologic data, distinguish between likely and unlikely paleogeographic relationships. The lack of signature Gondwanan zircons in the Smith River Allochthon suggests that it likely did not originate from Gondwana, but probably came from Laurentia's eastern margin. This study implies that the origin of the outboard, and much larger, Piedmont terrane within the southern Appalachians is not constrained, despite many studies that have proposed a Gondwanan affinity for it (e.g., Hibbard and Samson, 1995). More broadly, the paleogeography of the early Iapetus Ocean, the mechanisms of its formation, and the timing of its opening remain poorly constrained.

3. Terranes as tracers of Neoproterozoic–Cambrian paleogeography

During their geologically active lifetimes, terranes that originated along the northern margin of Gondwana (the so-callled "peri-Gondwanan terranes" such as Avalonia, Oaxaquia, and Cadomia) each have Neoproterozoic and Early Paleozoic histories that can provide critical constraints on paleocontinental reconstructions. Each terrane has a characteristic combination of basement isotopic signature, duration of arc or rift magmatism, and timing and style of deformation that tracks its tectonic evolution. These terrane records help to identify portions of the Neoproterozoic–Cambrian plate boundaries and find their paleogeographic context (e.g., Murphy et al., 2004).

Several contributions in this issue use key observations from terranes to suggest modifications to Neoproterozoic–Cambrian paleogeography. Murphy (2006) documents the interplay between ca. 620 and 605 Ma arc magmatism, extensional faulting and deformation in the Antigonish Highlands of Nova Scotia, providing a case example for the tectonic evolution of Avalonia from a subduction to a dominantly transform West Gondwanan plate boundary during the Neoproterozoic–Cambrian transition. On the basis of field mapping, whole rock geochemistry and Nd isotopes, Rogers et al. (2006) identify a possible ca. 563 Ma volcanic arc marker of continental Ganderia (Van Staal et al., 1998) basement in the Victoria Lake Supergroup of central Newfoundland, thus tracing the leading edge of the Ganderia peri-Gondwanan terrane. They argue that Ganderia, the Carolina terrane and the Charnwood Forest inlier of the British Midlands are built on isotopically similar crust that is distinctly older than that of Avalonia, and that these terranes all hosted arc magmatism well into the latest Neoproterozoic, marking continued subduction under Ganderia and associated terranes after similar magmatism had ceased in Avalonia. Rogers et al. (2006) also report younger ca. 511 Ma arc magmatism in the Victoria Lake Supergroup which they interpret to be an early product of Iapetan subduction as part of the Penobscot Arc built on Ganderia basement.

The Oaxaquia terrane likely forms the continental basement to much of eastern and central Mexico (Keppie, 2004), but its position in Neoproterozoic paleogeography is unknown. In the Novillo Gneiss, the northernmost exposure of Oaxaquia, Keppie et al. (2006) have produced U-Pb titanite and Ar-Ar hornblende and biotite data to constrain the Neoproterozoic post-Grenvillian cooling history of the terrane, and to date the intrusion of unmetamorphosed plume-related mafic dykes at ca. 546 Ma. The latter event is a newly recognized one for Oaxaquia, and is interpreted by Keppie et al. (2006) to represent the separation of Avalonia from Oaxaquia, taking Oaxaquia to have been located along the northern margin of Gondwana during Late Neoproterozoic to Early Cambrian time.

Fragments of the Neoproterozoic West Gondwanan margin are found throughout southern and central Europe. Four papers in this issue deal with the isotopic, magmatic and deformational/metamorphic history of portions of the Cadomian–Avalonian belt in Spain, southern Germany and Bulgaria. Valladares et al. (2006) report carbon, oxygen and strontium isotopic data for the Late Neoproterozoic Pastores carbonate section in central Iberia, noting that despite some evidence for alteration, the section retains the record of a negative

$\delta^{13}C$ excursion and maximum Sr isotope ratio that is comparable to that found immediately underlying the Ediacaran–Cambrian boundary worldwide. Etxebarria et al. (2006) lay out the architecture and major element geochemistry of mid-Cambrian rift volcanism and basin formation in the core of the Ossa-Morena Zone, southwestern Iberia. They interpret the subsidence and magmatism to have taken place during the beginning of true Rheic Ocean drift between Avalonia and the Armorica terrane assemblage of Cadomia.

Buschmann et al. (2006) investigate the Late Neoproterozoic and Early Cambrian dominantly marine siliciclastic rocks which bracket the Cadomian unconformity in the Saxo-Thuringian Zone of southern Germany, and infer a hiatus of 30–55 million years across the Precambrian–Cambrian boundary unconformity there. These strata record a switch from a ca. 566 Ma active continental margin distal setting to a ca. 520 Ma marine transform setting and a transition from a likely cooler to a warmer paleoclimate, similar to the interpreted Late Neoproterozoic to Cambrian features and paleogeography of the Armorician Massif, France and the Ossa-Morena Zone of Spain (Buschmann et al., 2006).

A Neoproterozoic–Early Cambrian continuation of the Avalonian–Cadomian belt of peri-Gondwanan terranes into eastern Europe is supported by new U-Pb geochronological data from the Sredna Gora Zone, central Bulgaria (Carrigan et al., 2006). Magmatic zircons from basement orthogneiss of the Sredna Gora Zone have an ~600 Ma emplacement age, and zircon cores from a leucosome dominantly range between 500 and 700 Ma age, with other cores grouping at Grenvillian, Paleoproterozoic and Late Archean ages, an age distribution typical of the ca. 1 Ga basement of Avalonian (but unlike the ca. 2 Ga Cadomian) terranes. Ubiquitous metamorphic zircon rims of ~336 Ma age mark Variscan metamorphism, suggesting that the peri-Gondwanan terranes of eastern Europe shared a common Late Neoproterozoic through mid-Paleozoic history with the Cadomian and particularly the Avalonian terranes (Carrigan et al., 2006).

4. Endings and beginnings

Neoproterozoic–Cambrian paleogeography is much debated, as evidenced in the diverse contributions to this issue. To explore the debate further we have included where possible a "question and answer" section following most papers in the issue, in which the authors are queried on technical aspects and on the wider implications of their work, as would happen at a meeting. We hope that this feature inspires further debate and fresh insights on the paleogeography of the time and on the tools we can use to decipher it.

As mooted above and as is apparent in this issue, Neoproterozoic paleogeography was probably not a simple progression over ~400 million years from one dominant supercontinent, Rodinia or Palaeopangea, to another, Gondwana. Perhaps the most significant development in recent debate on the Neoproterozoic–Cambrian paleogeography is the recognition of its similarities with that of the Mesozoic–Cenozoic Earth, including dispersed continents in relative motion and the mobility at various times of a substantial number of terranes (Powell and Pisarevsky, 2002; Cordani et al., 2003; Meert, 2003; Keppie et al., 2003; Murphy et al., 2004; Tohver et al., 2006). Unfortunately we do not have some of the tools that are available to Mesozoic–Cenozoic paleogeographers, such as an extant seafloor-spreading record or a well-developed biogeography to assist us in reconstructing the Neoproterozoic paleogeography. Rather than discourage further investigation, the realization of a more "complex" Neoproterozoic paleogeography instead calls us to place a great value on the synthesis of individual findings from paleomagnetism, geochronology, geochemistry and geology to infer past paleogeographic relationships and to recognize the record of geologic processes. We also know that the supercontinent Gondwana must form in a geologically reasonable way by Cambrian time, and that other possible constraints may be afforded by a growing understanding of Ediacaran–Cambrian biogeography (e.g., Waggoner, 1999; Meert and Lieberman, 2004), long-period global geodynamics (e.g., Burke and Torsvik, 2003; Evans, 2003), and the application of new tools such as the radiometric dating of diagenesis in Precambrian sedimentary rocks (Rassmussen, 2005).

This issue appears at a time when much of the easier work in more accessible and well exposed Neoproterozoic regions has been done (and it was not so easy!). We hope that this volume stimulates debate and inspires further Neoproterozoic–Cambrian endeavours, and we look forward to the discovery of fresh constraints upon the paleogeography, life and climate of this seminal interval in Earth history.

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Phil J.A. McCausland *
Department of Geological Sciences, University of Michigan, 2534 C.C. Little Building, Ann Arbor, MI 48109, USA

J. Brendan Murphy
Department of Earth Sciences, St. Francis Xavier University, Antigonish, NS, B2G 2W5 Canada

Conall MacNiocaill
Department of Earth Sciences, University of Oxford, Parks Road, Oxford OX1 3PR, United Kingdom

* Corresponding author. Present address: Department of Earth Sciences, University of Western Ontario, London, Ont., Canada N6A 5B7. Fax: +1 519 661 3198.
E-mail addresses: pmccausl@uwo.ca (P.J.A. McCausland), bmurphy@stfx.ca (J.B. Murphy), Conall.MacNiocaill@earth.ox.ac.uk (C. MacNiocaill)

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