Chuar Group of the Grand Canyon: Record of breakup of Rodinia, associated change in the global carbon cycle, and ecosystem expansion by 740 Ma

Karl E. Karlstrom* Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, New Mexico 87131, USA
Samuel A. Bowring Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
Carol M. Dehler Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, New Mexico 87131, USA
Andrew H. Knoll
Susannah M. Porter — Department of Organismic and Evolutionary Biology, Harvard University, Cambridge, Massachusetts 02138, USA
David J. Des Marais NASA Ames Research Center, Moffett Field, California 94035, USA
Arlo B. Weil Department of Geosciences, University of Michigan, Ann Arbor, Michigan 48109-1063, USA
Zachary D. Sharp
John W. Geissman
Maya B. Elrick
J. Michael Timmons
Laura J. Crossey — Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, New Mexico 87131, USA
Kathleen L. Davidek Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

ABSTRACT

The Chuar Group (~1600 m thick) preserves a record of extensional tectonism, ocean-chemistry fluctuations, and biological diversification during the late Neoproterozoic Era. An ash layer from the top of the section has a U-Pb zircon age of 742 ± 6 Ma. The Chuar Group was deposited at low latitudes during extension on the north-trending Butte fault system and is inferred to record rifting during the breakup of Rodinia. Shallow-marine deposition is documented by tide- and wave-generated sedimentary structures, facies associations, and fossils. C isotopes in organic carbon show large stratigraphic variations, apparently recording incipient stages of the marked C isotopic fluctuations that characterize later Neoproterozoic time. Upper Chuar rocks preserve a rich biota that includes not only cyanobacteria and algae, but also heterotrophic protists that document increased food web complexity in Neoproterozoic ecosystems. The Chuar Group thus provides a well-dated, high-resolution record of early events in the sequence of linked tectonic, biogeochemical, environmental, and biological changes that collectively ushered in the Phanerozoic Eon.

Keywords: Rodinia, Chuar Group, Grand Canyon, Neoproterozoic, C isotopes.

INTRODUCTION

The Neoproterozoic Era (1.0–0.54 Ga) was a time of dramatic change in the Earth system. Earth's lithosphere records the dispersal of Rodinia, the pre-Pangean supercontinent, with extensional tectonism on most continents (Dalziel, 1997). Carbon isotopes in marine carbonates and organic matter document secular variations in the carbon cycle that have few if any parallels in the Phanerozoic biosphere (Knoll et al., 1986; Kaufman and Knoll, 1995). Many of these pronounced C isotopic fluctuations are stratigraphically associated with glaciogenic sedimentary rocks (Kaufman et al., 1997) and have been interpreted in terms of an alternation of global glaciation and greenhouse warming that is without younger counterpart (Hoffman et al., 1998). The late Neoproterozoic Era is further marked by an evolutionary radiation of eukaryotic organisms that culminated in the diversification of animals (Knoll, 1992a). Because these events occurred more or less synchronously, it is reasonable to view them as linked components of the Earth surface system. However, attempts to model Earth system interrelationships depend on well-dated stratigraphic sections that record tectonic, biogeochemical, and paleontological information. The Chuar Group provides one such record.

SYNEXTENSIONAL DEPOSITION: A LINK TO THE BREAKUP OF RODINIA

The Chuar Group (Fig. 1), exposed only in the Grand Canyon (~150 km^2), accumulated in an intracratonic rift basin of unknown original extent. On the basis of stratigraphic correlations to the Death Valley region (Link et al., 1993) and parallelism of syndepositional faults to the western margin of Laurentia, we argue that this was an intracratonic rift basin located inboard of the rifted margin. Structural and stratigraphic studies of the Chuar Group indicate that it was deposited synchronously with normal faulting on the north-trending Butte fault, as shown by intraformational faults and development and tightening with depth of a Neoproterozoic growth syncline (Timmons et al., 2000).

Chuar extension was linked in time and style with rifting events observed globally (Fig. 1). In northwestern Laurentia, widespread mafic magmatism at 762–723 Ma accompanied deposition of rift sequences in the Mackenzie Mountains and lower Windermere Supergroups (Ross et al., 1995; Rainbird et al., 1996). The Adelaidean basin of Australia began as a series of intracratonic rifts that started opening before the 827 ± 6 Ma Gairdner dike swarm (Wingate and Giddings, 2000) and continued to accumulate sediments throughout the Neoproterozoic. Rifting of the South China craton was initiated with mafic dike swarms at 830–820 Ma, followed by sedimentation in an extensional basin beginning by 748 ± 12 Ma (Li et al., 1999). In southern Africa, the Otavi carbonate platform accumulated sediment following a main pulse of rifting from 758 to 746 Ma (Hoffman et al., 1998). All of these rift-related packages contain glaciogenic sedimentary rocks and display large C isotope variations, underscoring the close interrelationships among global extensional tectonics, the carbon cycle, and Neoproterozoic climatic fluctuations.

GEOCHRONOLOGY OF THE CHUAR GROUP

Previous geochronologic data on the Chuar Group indicated only that it was younger than the underlying 1.1 Ga Unkar Group and older than the unconformably overlying Middle Cambrian Tapeats Formation (ca. 510 Ma).

---

*E-mail: kek1@unm.edu.

Data Repository item 200066 contains additional material related to this article.

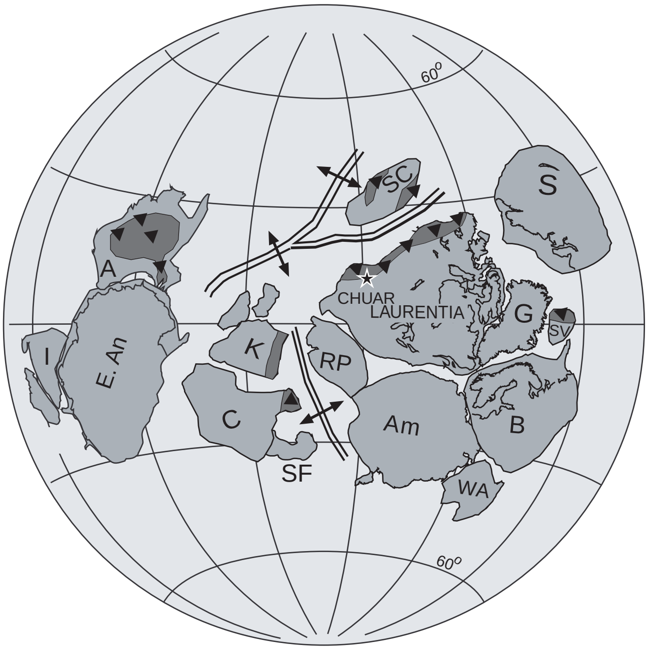

Figure 1. Speculative view of continent configuration during fragmentation of near equatorial Rodinia ca. 750 Ma (modified from reconstructions of Li et al., 1995; Dalziel, 1997; Weil et al., 1998; Karlstrom et al., 1999). A—Australia, E. An—East Antarctica, Am—Amazonia, B—Baltica, C—Congo, G—Greenland, I—India, K—Kalahari, S—Siberia, SC—South China, SF—Sao Francisco, SV—Svalbard, RP—Rio de la Plata, WA—West Africa. Dark gray represents 800–700 Ma supracrustal successions in rift basins; triangles are locations of glaciogenic rocks. Orientation and latitude of East Gondwana (Australia–East Antarctica–India–Madagascar) is based on paleomagnetic data from Mundine Well dike swarm (Wingate and Giddings, 2000); that of Laurentia is based on data from Chuar Group (Elston et al., 1993; this paper) and lower Rapitan Group (Park, 1997). Paleolatitude of South China is based on data reported by Li and Powell (1999); paleolatitude of Congo craton is based on data reported by Meert et al. (1995).

For this study, we sampled a 1-cm-thick ash layer from the uppermost Chuar Group, on Nankoweap Butte. A sample of ~0.5 kg yielded a population of 50–150-μm-long, doubly terminated, prismatic, highly fractured zircons, many of which contain abundant inclusions. Eight single-grain analyses (Fig. 2; Table 1[1]) define a normally discordant array (^{207}Pb/^{206}Pb > ^{207}Pb/^{235}U > ^{206}Pb/^{238}U) with an upper intercept date of 742 ± 6 Ma. We interpret this as the depositional age of the uppermost Chuar Group. The age of the lower part of the Chuar Group is unknown. However, the succession is apparently internally conformable and contains shallow-marine sedimentary rocks. Thus, assuming mean Phanerozoic sediment-accumulation rates of 20–30 m/m.y. for comparable environments (Sadler, 1981), we speculate that the base of the Chuar Group is younger than ca. 800 Ma.

PALEOMAGNETISM OF THE CHUAR GROUP: EQUATORIAL DEPOSITION DURING RIFTING OF RODINIA

More than 60 sites were collected from hematitic sandstone and siltstone throughout the Chuar Group. Seven to ten samples from each site were thermally demagnetized to 700 °C; in all cases, magnetic remanence was dominated by hematite. About two-thirds of the sites carry what we interpret to be a primary or near-primary characteristic magnetization on the basis of a positive paleomagnetic fold test using the syndepositional Chuar syncline. Magnetization is west and shallow down (interpreted to be normal polarity based on a comparison with Cambrian-Ordovician magnetizations from North America), or east and shallow up (reversed polarity). The inclination data yield an inferred paleolatitude of ~5°N for the lower Chuar Group and ~10°N for the upper Chuar Group. These data are in broad agreement with results reported by Elston et al. (1993) and are important for helping define the orientation and position of Laurentia during fragmentation of the near-equatorial Rodinia supercontinent (Fig. 1).

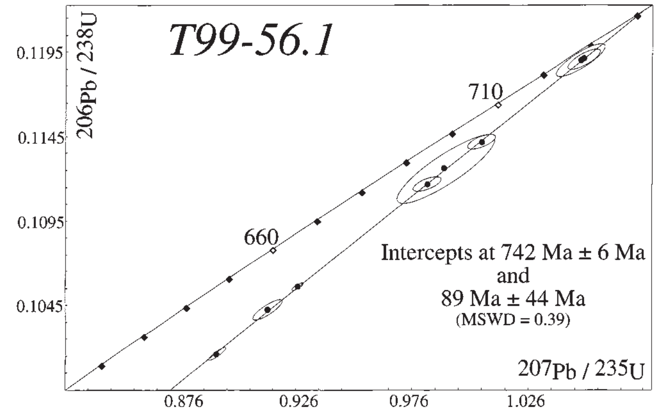

Figure 2. Concordia plot of zircons from Chuar Group. Analytical details follow Bowring et al. (1998). MSWD—mean square of weighted deviates. Data (Table 1) are available from GSA Data Repository (see footnote 1).

STRATIGRAPHY AND MARINE DEPOSITIONAL SETTING: A LINK TO GLOBAL OCEANS

The Chuar Group (~1600 m) consists of variegated mudrocks interbedded with laterally extensive meter-scale dolomite and sandstone beds (Fig. 3). Fine-grained dolomites display microbial laminae, domal to columnar stromatolites, flat-pebble conglomerates, ripple cross-laminae, and various scales of desiccation cracks. Sandstones contain asymmetric and symmetric ripplemarks (with local mudcracked mud drapes), planar-tabular cross-beds with local reverse-flow indicators, and planar horizontal laminae. Mudrocks are commonly organic rich (total organic carbon [TOC] 0.01–8 wt%; Cook 1991; Table 2; see footnote 1) and contain abundant marine microfossils. The combination of tidal sedimentary structures, marine fossils within mudrocks, and centimeter- to meter-scale interbedding of all facies suggests deposition in shallow subtidal to intertidal-supratidal marine environments. The intimate interbedding of shallow subtidal-supratidal dolomite and sandstone with mudrock facies indicates that water depths likely did not exceed a few tens of meters during most of Chuar deposition.

The overlying Sixtymile Formation (40–60+ m) may mark a base-level change. It is composed of thinly bedded, white to red siltstone and sandstone that is variably brecciated and contorted by soft-sediment folds. The siltstone is incised at its top by 10-m-scale, steep-walled channels filled with coarse intraformational breccia and conglomerate and red cross-bedded sandstone. This unit has been interpreted to mark tectonism and slumping on the adjacent Butte fault (Elston, 1979), perhaps as the growth fault became emergent (Timmons et al., 2000). Alternatively or additionally, it could mark glacio-eustatic controls on deposition, similar to the sea-level fall and canyon incision associated with other Neoproterozoic glacial sequences (Levy et al., 1994). The Sixtymile Formation is undated, but has been correlated with the transition beds of the Pahrump Group and with glaciogenic rocks of the Windermere Supergroup (Link et al., 1993).

C ISOTOPE STRATIGRAPHY OF THE CHUAR GROUP: LARGE-MAGNITUDE OCEAN-CHEMISTRY FLUCTUATIONS

C isotope data for bulk organic matter ($\delta^{13}C_{org}$) were obtained from black and gray mudrocks distributed throughout the Chuar Group (Fig. 3).

---

[1] GSA Data Repository item 200066, Tables 1–3, U-Pb zircon, O and C isotope, and TOC data, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder CO 80301-9140, editing@geosociety.org, or at www.geosociety.org/pubs/ft2000.htm.

The $\delta^{13}C_{org}$ data show several pronounced, relatively high-frequency fluctuations in the lower Galeros Formation, relatively invariant values in the upper Galeros, and a marked (13‰) excursion in the Kwagunt Formation. C isotope values from interbedded carbonates ($\delta^{13}C_{carb}$) are more scattered, especially in the Kwagunt Formation, where thin, organic-rich carbonates are intercalated among carbonaceous shales. Least diagenetically altered samples generally mirror the trends in $\delta^{13}C_{org}$ values, with values that fall within the envelope of $\delta^{13}C_{org}$ plus 28‰ ± 2‰ empirically determined for other Neoproterozoic carbonates (Fig. 3; Knoll et al., 1986). Thus, the broad pattern of stratigraphic variation in $\delta^{13}C_{org}$ values probably records, at least qualitatively, secular variations in the C isotope composition of Chuar seawater. Geochemical tests for diagenetic alteration lend further support to this conclusion. Marker beds show lateral variability of <0.5‰ across the 150 km^2 study area; the average $\delta^{18}O_{carb} > -4$ (Table 3; see footnote 1), and H/C > 0.49 (Strauss and Moore, 1992).

The magnitude of C isotope variation in the Chuar Group is similar to that in successions that underlie Sturtian glacial deposits elsewhere. Comparably large $\delta^{13}C_{carb}$ variability has been demonstrated in the upper Beck Springs Dolomite, California (Prave, 1999), and the 723–781 Ma upper Shaler and Coats Lake Groups, northwestern Canada (Strauss and Moore, 1992; Rainbird et al., 1996; Kaufman and Knoll, 1995). Carbonates in the pre-Sturtian Burra Group, South Australia, that are 2–3 km stratigraphically above the 802 ± 10 Ma Rook Tuff vary from +7‰ to –5‰ (Walter et al., 2000). Thus, C isotope fluctuations seen in the Chuar Group and elsewhere indicate that the global biogeochemical transition from an earlier pattern of moderate C isotope variability (Knoll et al., 1995; Kah et al., 1999) to one of isotopic extremes began by ca. 800–740 Ma in the context of the rifting of Rodinia.

CHUAR GROUP FOSSILS: DIVERSIFICATION OF ECOSYSTEMS AND FIRST HETEROTROPHIC PROTISTS

The Chuar Group has been known to be fossiliferous since the discovery of the millimeter-scale compression fossil *Chuaria circularis* by Walcott (1899). Thought to be the reproductive cysts of eukaryotic protists, *Chuaria* occurs in large populations in carbonaceous siltstones throughout the Chuar Group (Ford and Breed, 1973). A greater diversity of acritarchs is confined to a few mudstone horizons in the Awatubi Member (Vidal and Ford, 1985). Cyanobacteria and large filaments possibly made by eukaryotic algae occur in upper Chuar cherts and shales, respectively (Schopf et al., 1973; Horodyski and Bloeser, 1983); however, an abundance of vase-shaped microfossils (Bloeser, 1985) marks this assemblage as special. Vase-shaped microfossils are widely distributed in Neoproterozoic rocks, but until now both their absolute age and their phylogenetic relationships have been uncertain. Huge populations of pyritized vase-shaped microfossils found in early diagenetic dolomite nodules near the top of the Chuar Group preserve details of morphology and test composition that identify these fossils as testate amoebae (Porter and Knoll, 2000; see also Schopf, 1992), providing unambiguous evidence of heterotrophic protists in pre-Ediacaran rocks. All vase-shaped microfossil assemblages from successions characterized by C isotope chemostratigraphy have first appearances that postdate the onset of markedly positive $\delta^{13}C$ values. Vase-shaped microfossils may thus provide proxies for a broader, environmentally facilitated increase in the trophic complexity of Neoproterozoic ecosystems—an expansion that may also have included microscopic ancestral animals (Porter and Knoll, 2000).

DISCUSSION

Our new date for the Chuar Group improves the geochronological constraints on Neoproterozoic successions and events well beyond the Grand Canyon. In particular, our multidisciplinary study provides a globally significant record that confirms and extends an emerging picture of broadly synchronous rifting, onset of high-amplitude C isotope fluctuations, and increase in biologic diversity from ca. 800 to 740 Ma.

Breakup of the postulated supercontinent may have involved several pulses of extension. One pulse seems to be recorded by the deposition of the Windermere Supergroup and lower Pahrump Group on the western margin of Laurentia and the formation of the intracratonic Chuar basin ca. 800–740 Ma. The breakup of the dominantly equatorial supercontinent provided widespread conditions favoring organic carbon burial and initiated the coupled biogeochemical and climatic events that characterize the late Neoproterozoic Era. Both the onset of rifting and the duration of

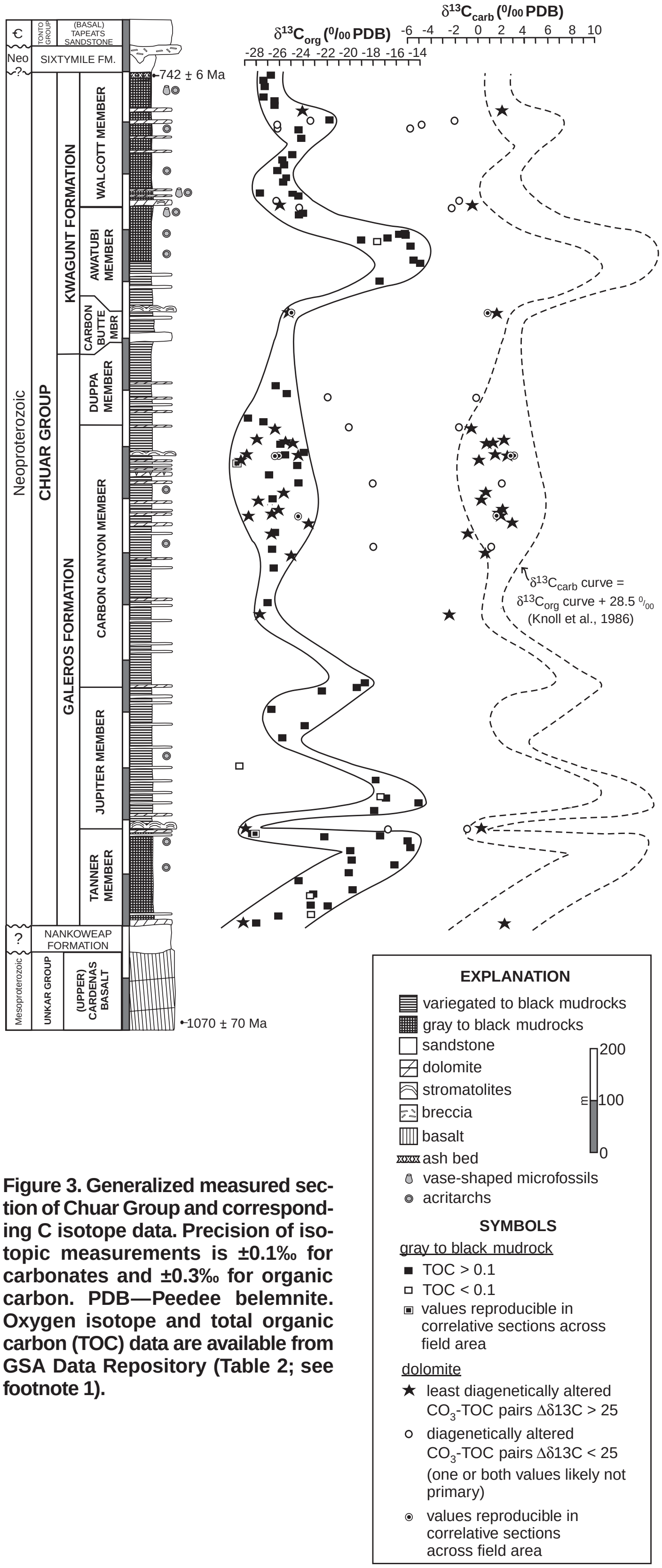

Figure 3. Generalized measured section of Chuar Group and corresponding C isotope data. Precision of isotopic measurements is ±0.1‰ for carbonates and ±0.3‰ for organic carbon. PDB—Peedee belemnite. Oxygen isotope and total organic carbon (TOC) data are available from GSA Data Repository (Table 2; see footnote 1).

progressive or episodic rifting (perhaps from 800 to 550 Ma) seem to coincide with the onset and duration of the most pronounced Neoproterozoic C isotope fluctuations.

This period (ca. 800–740 Ma) of the Neoproterozoic may have set the stage for an expansion of globe-girdling ice sheets in the late Neoproterozoic (Hoffman et al., 1998), as well as the evolution of animal life (Knoll, 1992b). Large negative C isotope shifts during the culminating events of this interval, near the end of the Neoproterozoic, have been interpreted as a record of global glaciations. In contrast, marked positive C isotope shifts at the time of Chuar sedimentation occurred in concert with rifting, but with no direct evidence for glaciation. Thus, the role of climate in driving Neoproterozoic carbon cycle changes appears to be superimposed on a longer lasting set of tectonic forcing factors.

ACKNOWLEDGMENTS

Research was supported by National Science Foundation grant EAR-9706541 (to Karlstrom, Elrick, Geissman, Bowring, and Knoll), the Conoco Corporation, Ben Donegan, NASA Astrobiology Institute (to Des Marais), Geological Society of America, Colorado Scientific Society, Society for Sedimentary Geology, the University of New Mexico Wanek Awards and Graduate Fellowship (to Dehler), University of Michigan Scott Turner Fund (to Weil), and Grand Canyon National Park. The paper benefited from reviews by Chris Powell, Paul Hoffman, and John Rogers.

REFERENCES CITED

Bloeser, B., 1985, *Melanocyrillium*, a new genus of structurally complex Late Proterozoic microfossils from the Kwagunt Formation (Chuar Group), Grand Canyon, Arizona: Journal of Paleontology, v. 59, p. 741–765.

Bowring, S.A., Erwin, D.H., Jin, Y.G., Martin, M.W., Davidek, K., and Wang, W., 1998, U-Pb zircon geochronology and tempo of the end-Permian mass extinction: Science, v. 280, p. 1039–1045.

Cook, D.A., 1991, Sedimentology and shale petrology of the Upper Proterozoic Walcott Member, Kwagunt Formation, Chuar Group, Grand Canyon, Arizona [M.S. thesis]: Flagstaff, Northern Arizona University, 128 p.

Dalziel, I.W.D., 1997, Overview: Neoproteorozic-Paleozoic geography and tectonics: Review, hypothesis, environmental speculations: Geological Society of America Bulletin, v. 109, p. 16–42.

Elston, D.P., 1979, Late Precambrian Sixty Mile Formation and the orogeny at the top of the Grand Canyon Supergroup, northern Arizona: U.S. Geological Survey Professional Paper 1092, 20 p.

Elston, D.P., Link, P.K., Winston, D., and Horodyski, R.J., 1993, Correlations of Middle and Late Proterozoic successions, *in* Reed, J.C., Jr., et al., eds., Precambrian: Conterminous U.S.: Boulder, Colorado, Geological Society of America, Geology of North America, v. C-2, p. 468–487.

Ford, T.D., and Breed, W.J., 1973, Late Precambrian Chuar Group, Grand Canyon, Arizona: Geological Society of America Bulletin, v. 84, p. 1243–1260.

Hoffman, P.F., Kaufman, A.J., Halverson, G.P., and Schrag, D.P., 1998, A Neoproterozoic snowball Earth: Science, v. 281, p. 1342–1346.

Horodyski, R.J., and Bloeser, B., 1983, Possible eukaryotic filaments from the Late Proterozoic Chuar Group, Grand Canyon, Arizona: Journal of Paleontology, v. 57, p. 321–326.

Kah, L.C., Sherman, A.G., Narbonne, G.M., Knoll, A.H., and Kaufman, A.J., 1999, δ^{13}C stratigraphy of the Proterozoic Bylot Supergroup, Baffin Island, Canada: Implications for regional lithostratigraphic correlations: Canadian Journal of Earth Sciences, v. 36, p. 1–20.

Karlstrom, K.E., Harlan, S.S., Williams, M.L., McLelland, J., Geissman, J.W., and Åhäll, K.-I., 1999, Refining Rodinia: Geologic evidence for the Australian–western U.S. connection in the Proterozoic: GSA Today, v. 9, no. 5, p. 1–7.

Kaufman, A.J., and Knoll, A.H., 1995, Neoproterozoic variations in the C-isotope composition of seawater: Stratigraphic and biogeochemical implications: Precambrian Research, v. 73, p. 27–49.

Kaufman, A.J., Knoll, A.H., and Narbonne, G.M., 1997, Isotopes, ice ages, and terminal Proterozoic Earth history: National Academy of Sciences Proceedings, v. 94, p. 6600–6605.

Knoll, A.H., 1992a, The early evolution of eukaryotes: A geological perspective: Science, v. 256, p. 622–627.

Knoll, A.H., 1992b, Biological and biogeochemical preludes to the Ediacaran radiation, *in* Lipps, J.H., and Signor, P.W., eds., Origin and early evolution of the Metazoa: New York, Plenum Press, p. 53–84.

Knoll, A.H., Hayes, J.M., Kaufman, A.J., Swett, K., and Lambert, I.B., 1986, Secular variation in carbon isotope ratios from Upper Proterozoic successions of Svalbard and East Greenland: Nature, v. 321, p. 832–838.

Knoll, A.H., Kaufman, A.J., and Semikhatov, M.A., 1995, The Proterozoic carbon isotopic record: Mesoproterozoic carbonates from Siberia: American Journal of Science, v. 295, p. 823–850.

Levy, M., Christie-Blick, N., and Link, P.K., 1994, Neoproterozoic incised valleys of the eastern Great Basin, Utah and Idaho: Fluvial response to changes in depositional base level, *in* Dalrymple, R.W., et al., eds., Incised-valley systems: Origin and sedimentary sequences: Society for Sedimentary Geology Special Publication 51, p. 369–382.

Li, Z.X., and Powell, C.M., 1999, Paleomagnetic study of Neoproterozoic glacial rocks of the Yangzi block: Palaeolatitude and configuration of South China in the Late Proterozoic supercontinent: Precambrian Research, v. 94, p. 1–5.

Li, Z.X., Zhang, L., and Powell, C.M., 1995, South China in Rodinia: Part of the missing link between Australia–East Antarctica and Laurentia?: Geology, v. 23, p. 407–410.

Li, Z.X., Li, X.H., Kinny, P.D., and Wang, J., 1999, The breakup of Rodinia: Did it start with a mantle plume beneath South China?: Earth and Planetary Science Letters, v. 173, p. 171–181.

Link, P.K., Christie-Blick, N., Devlin, W.J., Elston, D.P., Horodyski, R.J., Levy, M., Miller, J.M.G., Pearson, R.C., Prave, A., Stewart, J.H., Winston, D., Wright, L.A., and Wrucke, C.T., 1993, Middle and Late Proterozoic stratified rocks of the western Cordillera, Colorado Plateau, and Basin and Range province, *in* Reed, J.C., Jr., et al., eds., Precambrian: Conterminous U.S.: Boulder, Colorado, Geological Society of America, Geology of North America, v. C-2, p. 463–596.

Meert, J.G., Van der Voo, R., and Ayub, S., 1995, Paleomagnetic investigation of the Neoproterozoic Gagwe lavas and Mbozi complex, Tanzania and the assembly of Gondwana: Precambrian Research, v. 74, p. 225–244.

Park, J.K., 1997, Paleomagnetic evidence for low-latitude glaciation during deposition of the Neoproterozoic Rapitan Group, Mackenzie Mountains, N.W.T., Canada: Canadian Journal of Earth Sciences, v. 34, p. 34–49.

Porter, S.M., and Knoll, A.H., 2000, Testate amoebae in the Neoproterozoic Era: Evidence from vase-shaped microfossils of the Chuar Group, Grand Canyon: Paleobiology, v. 26, p. 345–370.

Prave, A.R., 1999, Two diamictites, two cap carbonates, two δ^{13}C excursions, two rifts: The Neoproterozoic Kingston Peak Formation, Death Valley, California: Geology, v. 27, p. 339–342.

Rainbird, R.H., Jefferson, C.W., and Young, G.M., 1996, The early Neoproterozoic sedimentary succession B of northwestern Laurentia: Correlations and paleogeographic significance: Geological Society of America Bulletin, v. 108, p. 454–470.

Ross, G.M., Bloch, J.D., and Krouse, H.R., 1995, Neoproterozoic strata of the southern Canadian Cordillera and the isotopic evolution of seawater sulfate: Precambrian Research, v. 73, p. 71–99.

Sadler, P.M., 1981, Sediment accumulation rates and the completeness of stratigraphic sections: Journal of Geology, v. 89, p. 569–584.

Schopf, J.W., 1992, Evolution of the Proterozoic biosphere: Benchmarks, tempo and mode, *in* Schopf, J.W., and Klein, C., eds., The Proterozoic biosphere: A multidisciplinary study: Cambridge, UK, Cambridge University Press, p. 585–600.

Schopf, W.J., Ford, T.D., and Breed, W.J., 1973, Microorganisms from the late Precambrian of the Grand Canyon, Arizona: Science, v. 179, p. 1319–1321.

Strauss, H., and Moore, T.B., 1992, Abundances and isotopic compositions of carbon and sulfur species in whole rock and kerogen samples, *in* Schopf, J.W., and Klein, C., eds., The Proterozoic biosphere; a multidisciplinary study: Cambridge, UK, Cambridge University Press, p. 709–798.

Timmons, M.J., Karlstrom, K.E., Dehler, C.M., Geissman, J.W., and Heizler, M.T., 2000, Proterozoic multistage (~1.1 and ~0.8 Ga) extension in the Grand Canyon Supergroup and establishment of northwest and north-south tectonic grains in the southwestern United States: Geological Society of America Bulletin (in press).

Vidal, G., and Ford, T.D., 1985, Microbiotas from the Late Proterozoic Chuar Group (Northern Arizona) and Uinta Mountain Group (Utah) and their chronostratigraphic implications: Precambrian Research, v. 28, p. 349–389.

Walcott, C.D., 1899, Precambrian fossiliferous formations: Geological Society of America Bulletin, v. 10, p. 199–244.

Walter, M.R., Veevers, J.J., Calver, C.R., Gorgan, P., and Hill, A.C., 2000, Dating the 840–544 Ma Neoproterozoic interval by isotopes of strontium, carbon and sulfur in seawater, and some interpretive models: Precambrian Research, v. 100, p. 371–433.

Weil, A.B., Van der Voo, R., Niocaill, C.M., and Meert, J.G., 1998, The Proterozoic supercontinent Rodinia: Paleomagnetically derived reconstructions for 1100 to 800 Ma: Earth and Planetary Science Letters, v. 154, p. 13–24.

Wingate, M.T.D., and Giddings, J.W., 2000, Age and paleomagnetism of the Mundine Well dike swarm: Implications for an Australia-Laurentia connection at 755 Ma: Precambrian Research, v. 100, p. 335–358.

Manuscript received November 16, 1999
Revised manuscript received March 27, 2000
Manuscript accepted April 7, 2000