port some metal grains out of a convective downdraft (into an updraft) before they are brought down to the midplane. The diffusivity of a particle in a convective eddy is $k \approx l_m v_{conv}$, and the turnover time of the eddy is comparable to l_m/v_{conv}, so that particles can diffuse about one mixing length. Let Δr be the radial width of the convection cell. The fraction of particles in a downdraft that diffuses outward and into an adjacent updraft before falling halfway to the midplane is $0.5x[1 - \mathrm{erf}(0.28\Delta r/l_m)]$. If $\Delta r = l_m$, this fraction is about one-third (0.345). Of this fraction of particles that diffuses into the neighboring updraft, ~50% will be transported to a downdraft even farther away, and the process can repeat. The width of a convection cell is likely to be about one mixing length (*29*), and we assume that $\Delta r = l_m = H$ (yielding $t_{growth} = 15$ days). In this case, particles must migrate outward through about three updrafts and three downdrafts (~0.3 AU) before escaping safely to cooler regions. The fraction that does so is $(0.5)^3(0.345)^3 = 5 \times 10^{-3}$. Thus, turbulence induced by convection can transport some Fe,Ni metal grains outward from the sun without sweeping them all the way to the midplane. These particles would not experience temperatures high enough to be vaporized or become homogenized by solid-state diffusion. The fraction of Fe,Ni metal grains that in this way retain their zoning is consistent with the observed relative abundance of zoned metal grains in CH chondrites (10^{-4} to 10^{-2}).

The high temperatures and the high heat flux implied in our model require a high mass flux ($dM/dt = 10^{-6}$ $M_\odot$ year^{-1}), formation close to the sun ($r \leq 1$ AU), or both.

References and Notes

1. J. N. Grossman, in *Meteorites and the Early Solar System*, J. F. Kerridge and M. S. Matthews, Eds. (Univ. of Arizona Press, Tucson, AZ, 1988), pp. 680–696.
2. G. E. Lofgren, in *Chondrules and the Protoplanetary Disk*, R. E. Hewins, R. H. Jones, E. R. D. Scott, Eds. (Cambridge Univ. Press, Cambridge, 1996), pp. 187–196.
3. S. Weinbruch *et al.* [*Meteorit. Planet. Sci.* **32**, 138 (1997)] concluded that the lower limit on chondrule cooling rates is 10 K hour^{-1}. However, chondrule cooling rates near the lower limit have only been determined for relatively rare granular-olivine-pyroxene chondrules studied in the carbonaceous chondrite Allende. Porphyritic chondrules, which all have cooling rate estimates >100 K hour^{-1}, are the most abundant type of chondrules by far and are considered the most representative of the chondrule-forming process.
4. L. Grossman and J. W. Larimer, *Rev. Geophys. Space Phys.* **12**, 71 (1974).
5. G. J. MacPherson, D. A. Wark, J. T. Armstrong, in *Meteorites and the Early Solar System*, J. F. Kerridge and M. S. Matthews, Eds. (Univ. of Arizona Press, Tucson, AZ, 1988), pp. 746–807.
6. E. Stolper and J. M. Paque, *Geochim. Cosmochim. Acta* **50**, 1785 (1986).
7. L. Grossman and E. Olsen, *Geochim. Cosmochim. Acta* **38**, 173 (1974).
8. W. R. Kelly and J. W. Larimer, *Geochim. Cosmochim. Acta* **41**, 93 (1977).
9. Iron-nickel metal, which is an important component in chondritic meteorites, is thermodynamically predicted to form by gas-solid condensation from a gas of solar composition at temperatures between 1450 and 1100 K and pressures of 10^{-3} to 10^{-5} bar. With decreasing gas temperature, the condensing metal is inferred to have decreasing Ni (30 to 5 wt %) and Co (0.8 to 0.2 wt %) concentrations (with a solar Co/Ni ratio) and increasing Cr (0 to 0.9 wt %) and Fe (70 to 95 wt %) concentrations. However, metal grains in most types of chondrites have subsequently experienced substantial secondary processing (e.g., melting, thermal metamorphism, and/or oxidation), which caused redistribution of Fe, Ni, Co, and Cr that partially or totally erased these chemical signatures of condensation.
10. H. Y. McSween, *Geochim. Cosmochim. Acta* **41**, 477 (1977).
11. B. Zanda, M. Bourot-Denise, C. Perron, *Lunar Planet. Sci. Conf.* **22**, 1543 (1991).
12. M. S. Lee, A. E. Rubin, J. T. Wasson, *Geochim. Cosmochim. Acta* **56**, 2521 (1992).
13. A. Meibom *et al.*, *J. Geophys. Res.* **104**, 22053 (1999).
14. M. K. Weisberg and M. Prinz, in *24th Symposium on Antarctic Meteorites, NIPR, Tokyo* (National Institute for Polar Research, Tokyo, 1999), pp. 187–189.
15. An origin of the zoned Fe,Ni metal grains in CH chondrites by reduction of silicates during chondrule formation can be ruled out because (i) at igneous temperatures (>1600 K) during chondrule formation, solid-state diffusion of Fe, Ni, Co, and Cr is so rapid that zoned Fe,Ni metal grains, which typically are 100 μm in radius, would become homogenized on a time scale of tens of minutes, comparable to the cooling time scale of most chondrules, and (ii) zoned Fe,Ni metal grains have never been observed inside chondrules.
16. D. E. Sanders and A. E. DePristo, *Surf. Sci.* **254**, 341 (1991).
17. The probability of sticking of metal atoms with thermal kinetic energies on a metal surface is nearly unity. The metal atoms become strongly accelerated as they approach the surface because of a deep (several eV) attractive well. When striking the surface, the atoms lose their kinetic energy (~0.2 eV) to the lattice and are trapped. This does not preclude that some Fe atoms can desorp (leave the surface) at some later time because of thermal vibrations in the crystal lattice. The rate of desorption can be estimated from the vapor pressure of Fe at the temperatures in question. At 1370 K, the vapor pressure of Fe is ~10^{-7} bar, only a small fraction of the partial pressure of Fe in the nebula gas. Although desorption of Fe atoms from the growing grains does take place, it happens at a relatively low rate compared with the rate of bombardment (Z) and does not substantially slow down the growth of the metal grain.
18. E. Anders and N. Grevesse, *Geochim. Cosmochim. Acta* **53**, 197 (1989).
19. D. C. Dean and J. I. Goldstein, *Metall. Trans.* **17A**, 1131 (1986).
20. The diffusion coefficients of Ni, Co, and Cr in γ-Fe are essentially identical, with Ni being slightly faster [D. R. Lide, Ed., *Handbook of Chemistry of Physics* (CRC Press, Boca Raton, FL, ed. 79, 1981)].
21. R. Kippenhahn and A. Weigert, *Stellar Structure and Evolution* (Springer-Verlag, Berlin, 1990).
22. J. B. Pollack *et al.*, *Astrophys. J.* **421**, 615 (1994).
23. A. P. Boss and J. A. Graham, *Icarus* **106**, 168 (1993).
24. L. L. Hood and D. A. Kring, in *Chondrules and the Protoplanetary Disk*, R. E. Hewins, R. H. Jones, E. R. D. Scott, Eds. (Cambridge Univ. Press, Cambridge, 1996), pp. 265–276.
25. D. C. Lin and J. Papaloizou, in *Protostars and Planets II*, D. C. Black and M. S. Matthews, Eds. (Univ. of Arizona Press, Tucson, AZ, 1985), pp. 981–1072.
26. K. R. Bell, P. M. Cassen, H. H. Klahr, T. Henning, *Astrophys. J.* **486**, 372 (1997).
27. J. W. Larimer, in *Meteorites and the Early Solar System*, J. F. Kerridge and M. S. Matthews, Eds. (Univ. of Arizona Press, Tucson, AZ, 1988), pp. 375–389.
28. M. Rozyczka, P. Bodenheimer, K. R. Bell, *Astrophys. J.* **423**, 736 (1994).
29. H. H. Klahr, T. Henning, W. Kley, *Astrophys. J.* **514**, 325 (1999).
30. J. N. Cuzzi, A. R. Dobrovolskis, R. C. Hogan, in *Chondrules and the Protoplanetary Disk*, R. H. Hewins, R. H. Jones, E. R. D. Scott, Eds. (Cambridge Univ. Press, Cambridge, 1996), pp. 35–43.

31. This collaboration between meteoriticists and astrophysicists was spurred by the 1999 Gordon Research Conference (Origins of Solar Systems), which brought together researchers from both disciplines in a highly inspiring scientific environment. Our work was supported by NASA grants 5-4212 (K. Keil, P.I.) and NAGW 3451 (J. A. Wood, P.I.) and NASA's Origins of Solar Systems program (J. Cuzzi, P.I.). A.M. is grateful for support from the Danish Natural Science Research Council. S.J.D. was supported by a National Research Council Research Associateship. We appreciate illuminating discussions with R. Bell, H. Klahr, A. Showman, A. Luntz, F. Besenbacher, T. Fagan, E. Scott, and J. Taylor.

7 December 1999; accepted 2 March 2000

Age of Neoproterozoic Bilatarian Body and Trace Fossils, White Sea, Russia: Implications for Metazoan Evolution

M. W. Martin,[1]* D. V. Grazhdankin,[2]† S. A. Bowring,[1] D. A. D. Evans,[3]‡ M. A. Fedonkin,[2] J. L. Kirschvink[3]

A uranium-lead zircon age for a volcanic ash interstratified with fossil-bearing, shallow marine siliciclastic rocks in the Zimnie Gory section of the White Sea region indicates that a diverse assemblage of body and trace fossils occurred before 555.3 ± 0.3 million years ago. This age is a minimum for the oldest well-documented triploblastic bilaterian *Kimberella*. It also makes co-occurring trace fossils the oldest that are reliably dated. This determination of age implies that there is no simple relation between Ediacaran diversity and the carbon isotopic composition of Neoproterozoic seawater.

The terminal Neoproterozoic interval is characterized by a period of supercontinent amalgamation and dispersal (*1, 2*), low-latitude glaciations (*3, 4*), chemical perturbations of seawater (*5–7*), and the first appearance and subsequent diversification of metazoans. Construction of a terminal Neoproterozoic biostratigraphy has been hampered by preserva-

tional, paleoenvironmental, and biogeographic factors (*5, 8*). Global biostratigraphic correlations within the Neoproterozoic are tenuous and rely on sparse numerical chronology, inferred stratigraphic diversity trends, and chemostratigraphy (*8–13*). As a result, the position of many late Neoproterozoic soft-bodied organisms in metazoan phylogeny remains controversial. Fundamental to a solution of this problem is an understanding of the temporal relationship between fossil occurrences with Ediacaran-type preservation and other body fossils, small shelly fossils, and trace fossils of burrowing organisms.

Although Ediacaran biotas are globally distributed, their temporal distribution is poorly known. Simple annuli and discs preserved below a glacial horizon in the Mackenzie Mountains of northwest Canada have been interpreted as possible metazoans and have been considered the oldest Ediacaran assemblage (*14*). Although their age is not constrained, they are commonly described as dating to 600 to 610 million years ago (Ma) (Fig. 1). The best-known diverse Ediacaran assemblages postdate the Varanger-Marinoan glaciation (*5, 8*). At Mistaken Point in eastern Newfoundland, fossils of soft-bodied organisms are dated at 565 ± 3 Ma (*15*). In the Ukraine, fossiliferous Upper Vendian strata of the Redkino Stage overlie volcanic rocks in Poland that are dated at 551 ± 4 Ma (*16, 17*). Ediacaran assemblages in the Nama Group in Namibia range from 548.8 ± 1 to 543.3 ± 1 Ma (*8*). Ediacaran-type fossils have been found together with *Treptichnus pedum* in what is described as Lower Cambrian sandstone of the Uratanna Formation in the Flinders Ranges, South Australia (*18*); in the Poleta Formation in the White-Inyo Mountains and Upper Wood Canyon Formation in the Death Valley region of California, USA (*19*); and in the Breivik Formation in arctic Norway (*20*). The two most abundant and diverse body and trace fossil assemblages—those from the Flinders Ranges (*10, 21*) in South Australia and White Sea coast in Russia (*22*), which account for 60% of the well-described Ediacaran taxa (*23*)—have neither numerical age nor direct chemostratigraphic constraints. In this report, we summarize the biostratigraphy and age of the Zimnie Gory exposure along the White Sea in Russia, and place the spectacularly preserved trace and body fossils, including the triploblastic bilaterian *Kimberella* (*24*), into a global chronostratigraphic framework.

Many exposures in the White Sea region contain known Ediacaran biotas; however, the best fossil occurences are found along shoreline cliffs at Zimnie Gory (Fig. 2). These unmetamorphosed and nondeformed (except for present-day cliff-face slumping) siliciclastic rocks belong to the uppermost Ust-Pinega Formation and form the northern flank of the Mezen Basin along the southeast flank of the Baltic Shield. The section records three upward-coarsening sequences: A, B, and C (Fig. 2).

Sequence A is 10 m thick and consists of planar- to wavy-laminated interbedded siltstone and claystone with fine- to medium-grained, cross-stratified sandstone. The sharp transition to maroon and variegated claystone of sequence B is marked by an unconformity that drapes an erosional undulatory relief on the top of sequence A. The lowest part of this

[1]Department of Earth Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139, USA. [2]Paleontological Institute, 123 Profsoyuznaya, Moscow, 117868, Russia. [3]Division of Geological and Planetary Sciences, 170-25, California Institute of Technology, Pasadena, CA 91125, USA.

*To whom correspondence should be addressed. E-mail: mwm@mit.edu
†Present address: Department of Earth Sciences, University of Cambridge, Cambridge, CB2 3EQ, UK.
‡Present address: Tectonics Special Research Centre, University of Western Australia, Nedlands, WA 6907, Australia.

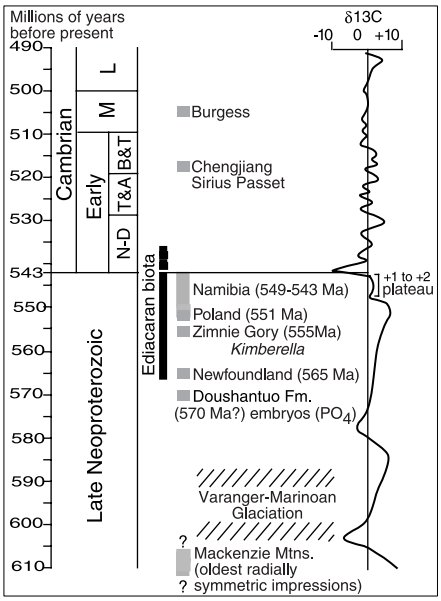

Fig. 1. Time scale showing temporal distribution of dated Ediacaran assemblages and several well-known Cambrian fossil assemblages (gray squares) and glaciations and carbon-isotopic curve. The ^{13}C isotopic curve is adopted from Knoll and Carroll (*35*). Phosphatized embryos that are similar to modern arthropods in the Doushantuo Formation of China are commonly cited as dated to 570 Ma (*31, 36*); however, there are no precise chronological constraints on this speculation of their age. Regional Siberian stage names are as follows: N-D, Nemakit-Daldynian; T&A, Tommotian and Atdabanian; and B&T, Botomian and Toyonia; M, Middle; L, Late.

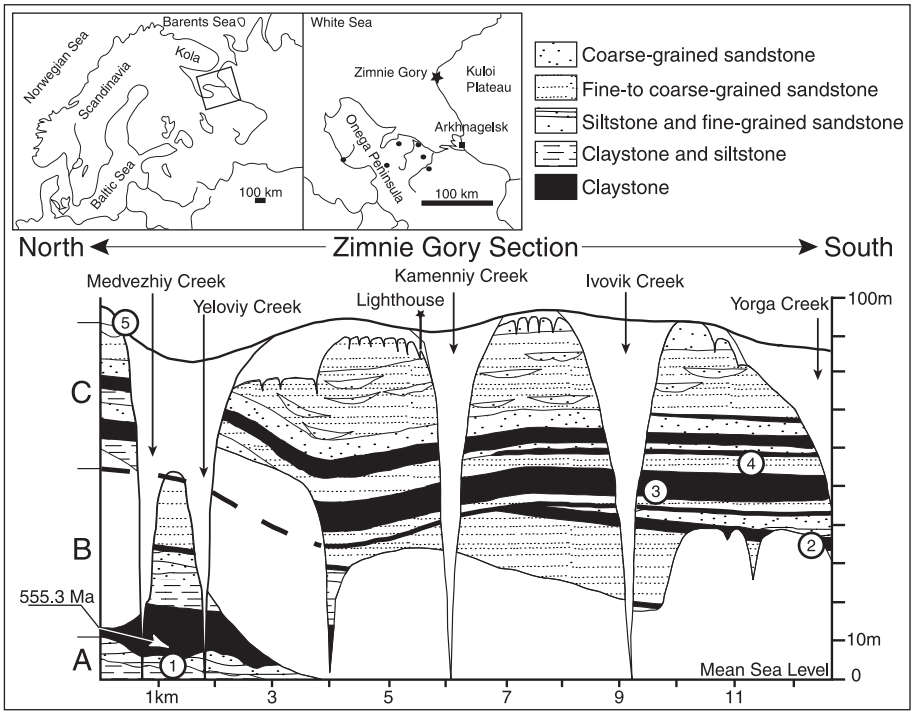

Fig. 2. Location map of the White Sea region in Russia and composite stratigraphic section of the Zimnie Gory section. Black dots on the inset map of the Onega Peninsula mark locations of known late Neoproterozoic fossils. Numbers on the stratigraphic section mark the positions of known fossils as follows: (**1**) *Charnia*, *Tribrachidium*, *Dickinsonia*, *Kimberella*, and *Eoporpita*; (**2**) *Charnia*; (**3**) *Dickinsonia*, *Kimberella*, *Parvancorina*, *Eoporpita*, and *Ovatoscutum*; (**4**) *Tribrachidium*, *Dickinsonia*, *Kimberella*, *Parvancorina*, *Eoporpita*, *Yorgia*, *Mawsonites*, and *Vendia*; and (**5**) *Tribrachidium*, *Dickinsonia*, *Kimberella*, and *Parvancorina*. Table 1 is a complete list of body and trace fossils from each sequence. Dated volcanic ash was collected between Medvezhiy and Yeloviy creeks near the base of sequence B.

claystone horizon contains a laterally discontinuous, pale-green volcanic ash that is 1 to 10 cm thick. The claystone passes upward into interbedded siltstone and claystone, which are overlain by channel and sheet siltstone and sandstone. The maximum thickness of sequence B is about 55 m. The top of sequence B is marked by an erosional unconformity that locally has cut 20 m of relief. Sequence C, locally attaining a thickness of 55 m, is composed of a basal thin horizon of flat-pebble to cobble conglomerate that is locally imbricated, which is overlain by interbedded sandstone, siltstone, and claystone. Grain size and sedimentary structures associated with sequences A, B, and C indicate a shallow, siliciclastic marine-dominated environment.

Table 1 lists body and trace fossils found in sequences A, B, and C. Body fossil diversities in sequences A and C are similar at the genus level; however, the assemblage of sequence C is noteworthy for its much greater diversity at the species level and for greater number of fossils. The trace fossils of sequence C appear to be more advanced forms than those found in sequence A. It is unclear whether these differences are real or are a function of limited exposure and sample bias in sequence A. Therefore, diversity as a means of comparing fossil assemblages in sequence A and C cannot be evaluated appropriately. Given their proposed distant paleogeographic positions at this time (*2*), the body and trace fossil assemblage of sequence C at Zimnie Gory compares well with that of the type-Ediacaran section in the Flinders Ranges, Australia, in terms of preservation style and composition at the level of genera and species (*10, 25, 26*). The remarkable similarity of these two assemblages could imply that they have closer paleogeographic affinities (*27*) not suggested by current paleogeographic reconstructions (*1, 2*).

We dated zircons from the volcanic ash in the lower part of the 15-m-thick claystone unit in the lower part of sequence B between Medvezhiy and Yeloviy creeks (Fig. 2). Zircons separated from this sample are euhedral, doubly terminated prisms up to 275 μm long, with aspect ratios ranging from 2:1 to 7:1; many are rich in inclusions. Four multigrain and 15 single-grain analyses are reported (Fig. 3) (*28*). With the exception of one multigrain analysis (three zircons), which we interpret to contain an older inherited component, the analyses yield a normally discordant array ($^{207}Pb/^{206}Pb > {}^{207}Pb/^{235}U > {}^{206}Pb/^{238}U$) anchored by one concordant analysis. A linear regression through these 18 data sets yields an upper intercept age of 555.4 ± 1.6 Ma [mean squared weighted deviation (MSWD) = 0.10] and a lower intercept indistinguishable from 0 Ma, suggesting that normal discordancy is a function of recent Pb loss. The 13 most precise analyses (% error in both of the Pb/U ratios ≤0.26) (Table 1) yield an upper intercept of 555.4 ± 1.7 Ma. Because the lower intercept in either case is indistiguishable from zero, the weighted mean of all the $^{207}Pb/^{206}Pb$ dates is interpreted as the best estimate for the age of the ash bed, 555.3 ± 0.3 Ma (MSWD = 0.10). The weighted mean of the 13 most precise $^{207}Pb/^{206}Pb$ dates is identical, at 555.3 ± 0.3 Ma (MSWD = 0.14).

This provides a minimum age for the oldest definitive triploblastic bilaterian, *Kimberella*, and the oldest well-developed trace fossils; and it documents that spectacularly diverse and preserved Ediacaran fossils formed more than 12 million years before the base of the Cambrian (Fig. 1). The oldest known bilaterian fossil, *Kimberella* (*24*), is only known from South Australia and the White Sea. *Kimberella* is an oval- to pear-

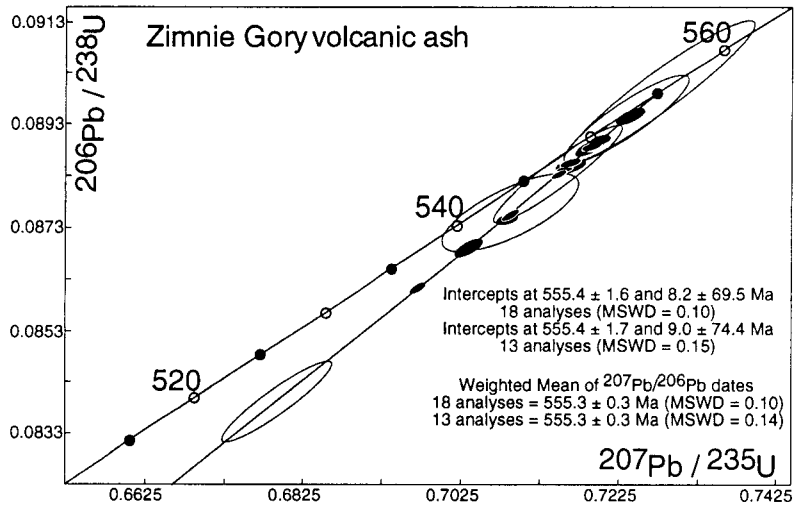

Fig. 3. U-Pb concordia diagram for Zimnie Gory volcanic ash.

Table 1. List of body and trace fossils present in sequences A, B, and C.

Sequence A	Sequence B	Sequence C
	Body fossils	
Anfesta	*Charnia*	*Anfesta*
Beltanelloides-like structures	*Ovatoscutum*	*Brachina*
Bonata	*Staurinidia*	*Cyclomedusa*
Charnia (Fig. 4A)	Molds of soft tubular structures; simple circular impressions	*Dickinsonia*
Cyclomedusa		*Ediacaria*
Dickinsonia (Fig. 4B)		*Eoporpita*
Ediacaria		*Inaria*
Eoporpita		*Irridinitus*
Hiemalora		*Kimberella*
Inaria		*Mawsonites*
Irridinitus		*Nemiana*
Kaisalia		*Parvancorina*
Kimberella (Fig. 4C)		*Ovatoscutum*
Nimbia		*Tribrachidium*
Protodipleurosoma		*Vendia*
Tribrachidium		*Yorgia*
Three-dimensional molds of tubular structures and others		Others, including numerous new forms
	Trace fossils	
Simple radial feeding burrows (Fig. 4D); backfilled burrows with circular path behavior; traces of crawling mollusk-like organism; fan-shaped sets of scratch marks (Fig. 4E)	Vertical burrows	Diverse radial feeding burrows; traces of crawling mollusk-like organism; fan-shaped sets of scratch marks; diverse vertical burrows; simple tunnels
	Enigmatic biological structures	
Yelovichnus		*Yelovichnus*
Palaeopascichnus		*Palaeopascichnus*
Intrites		*Intrites*

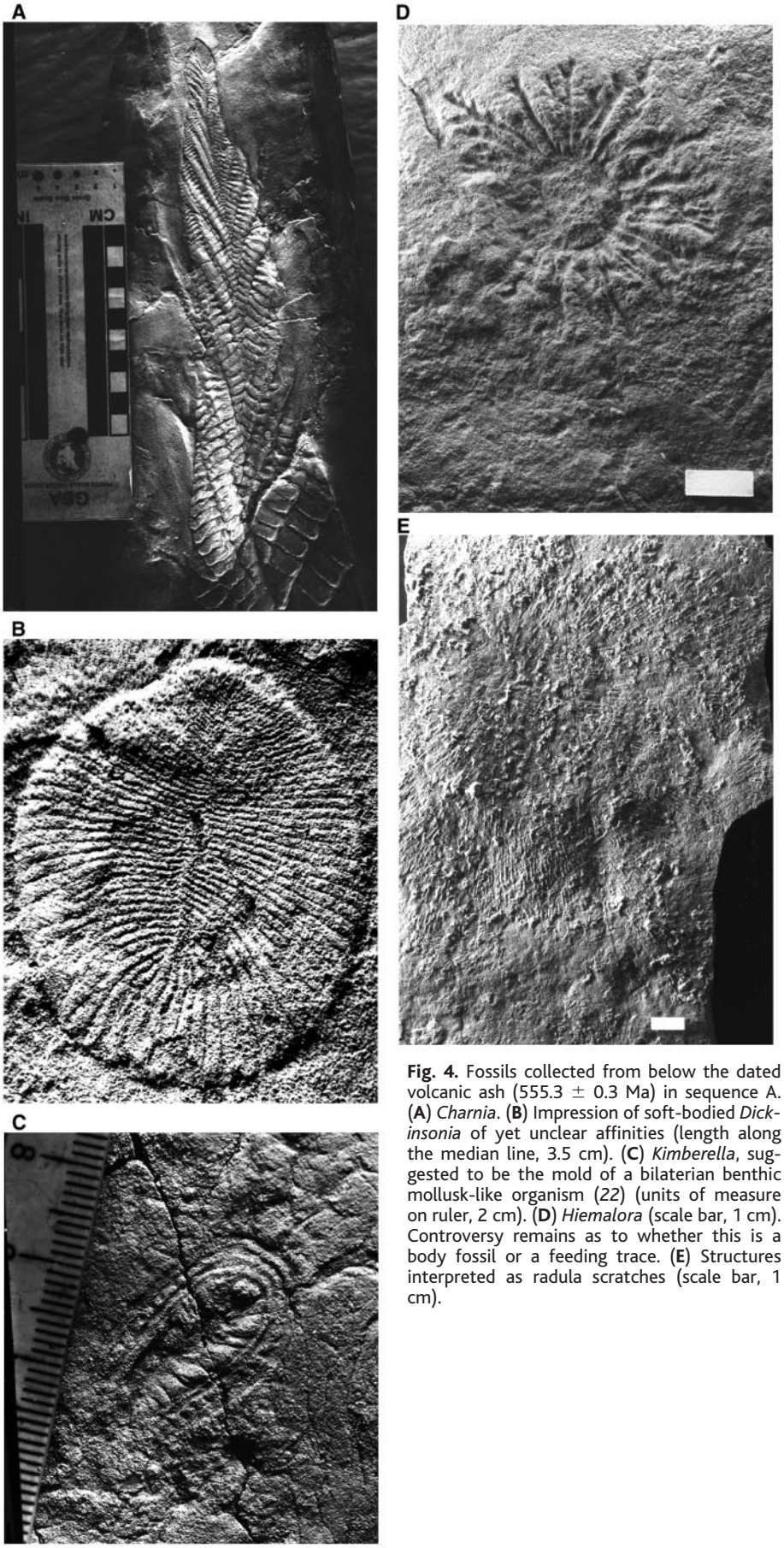

Fig. 4. Fossils collected from below the dated volcanic ash (555.3 ± 0.3 Ma) in sequence A. (**A**) *Charnia*. (**B**) Impression of soft-bodied *Dickinsonia* of yet unclear affinities (length along the median line, 3.5 cm). (**C**) *Kimberella*, suggested to be the mold of a bilaterian benthic mollusk-like organism (*22*) (units of measure on ruler, 2 cm). (**D**) *Hiemalora* (scale bar, 1 cm). Controversy remains as to whether this is a body fossil or a feeding trace. (**E**) Structures interpreted as radula scratches (scale bar, 1 cm).

shaped bilaterally symmetric fossil that ranges from 0.3 to 14 cm long and has several zones arranged concentrically with both soft and firm body parts (*24*) (Fig. 4C). Fedonkin and Waggoner (*24*) interpreted *Kimberella* as being more complex than a flatworm and having possible molluscan synapomorphies, such as a broad muscular foot. Seilacher (*29*) proposed that the radula scratches found in rocks of similar antiquity and lithology in South Australia (*30*) were made by a bilaterian (possibly *Kimberella*) during pendulum grazing, which is also a molluscan feature. Radula scratches (Fig. 3E) now found with *Kimberella* below the dated ash at Zimnie Gory support this interpretation. However, whether *Kimberella* at 555 Ma indicates that the protostome-deuterostome split is even older is not yet resolvable (*31*). Finally, our age determination places such characteristic late Neoproterozoic guide genera as *Charnia*, *Dickinsonia*, *Tribrachidium*, and *Kimberella* at least 6 million years before the Namibian assemblage (549 to 543 Ma) (*8*, *13*).

In addition to the radula scratches, complex trace fossils found below and above the dated ash (Fig. 4D) establish that metazoans capable of active crawling and burrowing were present by that time. These trace fossils probably require an animal with a morphologic grade more complex than cnidarians or flatworms (*31*).

This age also implies that there is no clear relationship between Ediacaran diversity and the terminal Neoproterozoic ^{13}C +1 to +2 plateau. (Fig. 1), in contrast to that suggested by Grotzinger *et al.* (*8*). Biostratigraphic correlation between Ediacaran localities is difficult because many localities contain limited numbers of specimens and few taxa. Biostratigraphic zonations, based on taxa diversity and carbon-isotope chemostratigraphy, have suggested (*8, 10, 13, 21, 25, 32*) that the sections in the Flinders Ranges and the White Sea are correlatives. Grotzinger *et al.* (*8*) noted that "very" diverse Ediacaran assemblages worldwide occur within the +1 to +2 ^{13}C interval, the so-called "+2 plateau" (Fig. 1), and demonstrated that the oldest part of this assemblage in Namibia was about 6 million years older than the Proterozoic-Cambrian boundary.

Detailed comparisons of taxa between Zimnie Gory and the type-Ediacaran in the Flinders Ranges suggest that they are coeval with our new age of 555.3 Ma. However, juxtaposition of the type-Ediacaran section with a composite carbon-isotopic curve (*10*) derived from correlative sections lacking Ediacaran fossils in southern and central Australia (*33*) suggests that it has chemostratigraphic affinity to the +1 to +2 ^{13}C interval dated at 549 to 543 Ma in southern Namibia (*8*) (Fig. 1). This observation requires that either the biostratigraphic correlation spans a

broad range (*34*) or is perhaps erroneous, or the chemostratigraphic correlation is incorrect. In any case, there is no simple relation between Ediacaran diversity and the terminal Neoproterozoic +1 to +2 ^{13}C plateau. The validity of characterizing the grade of Ediacaran faunal diversity [i.e., low, moderate, high, or very high diversity (*12*)] as a proxy for evolutionary hierarchy, and by inference higher biostratigraphic position, is not borne out by the new geochronologic data from the White Sea. It is clear that high-precision U-Pb geochronology will be the final arbitrator for global correlations.

References and Notes

1. P. F. Hoffman, *Science* **252**, 1409 (1991).
2. I. W. D. Dalziel, *Geol. Soc. Am. Bull.* **109**, 16 (1997).
3. J. L. Kirschivink, in *The Proterozoic Biosphere*, J. W. Schopf and C. Klein, Eds. (Cambridge Univ. Press, Cambridge, 1992), pp. 51–52.
4. P. F. Hoffman, A. J. Kaufman, G. P Halverson, D. P. Schrag, *Science* **281**, 1342 (1998).
5. A. H. Knoll and M. R. Walter, *Nature* **356**, 673 (1992).
6. S. M. Pelechaty, A. J. Kaufman, J. P. Grotzinger, *Geol. Soc. Am. Bull.* **108**, 992 (1996).
7. J. K. Bartley *et al.*, *Geol. Mag.* **135**, 473 (1998).
8. J. P. Grotzinger, S. A. Bowring, B. Z. Saylor, A. J. Kaufman, *Science* **270**, 598 (1995).
9. G. M. Narbonne *et al.*, *Can. J. Earth Sci.* **14**, 1277 (1987).
10. R. J. F. Jenkins, *Precambrian Res.* **73**, 51 (1995).
11. R. B. Macnaughton and G. M. Narbonne, *Palaios* **14**, 97 (1999).
12. G. M. Narbonne, A. J. Kaufman, A. H. Knoll, *Geol. Soc. Am. Bull.* **106**, 1281 (1994).
13. A. J. Kaufman and A. H. Knoll, *Precambrian Res.* **73**, 27 (1995).
14. H. J. Hofmann, G. M. Narbonne, J. D. Aitken, *Geology* **18**, 1199 (1990).
15. A. P. Benus, *Bull. N.Y. State Mus.* **463**, 8 (1988).
16. W. Compston *et al.*, *J. Geol. Soc. London* **152**, 599 (1995).
17. The new date (555.3 ± 0.3 Ma) reported here suggests that the Redkino rocks along the northern Russian platform predate the Volhyn Group volcanic rocks in Poland, suggesting that either the Redkino transgression is diachronous across the Russian platform or that the correlation between Polish volcanic rocks and the Volhyn Group in the Ukraine is incorrect.
18. S. Jensen *et al.*, *Nature* **393**, 567 (1998).
19. J. W. Hagadorn, C. M. Fedo, B. M. Waggoner, *J. Paleontol.* **74**, 554 (2000).
20. T. P. Crimes and D. McIlroy, *Geol. Mag.* **136**, 633 (1999).
21. R. C. Sprigg, *Trans. R. Soc. South Aust.* **71**, 212 (1947).
22. M. A. Fedonkin, *Belomorskaya Biota Venda* (Nauka, Moscow, 1981).
23. Only those taxa with "good" ratings (one, two, or three stars) were used in estimating reliable taxa reported by B. E. Runnegar, in *The Proterozoic Biosphere*, J. W. Schopf and C. Klein, Eds. (Cambridge Univ. Press, Cambridge, 1992), pp. 999–1007.
24. M. A. Fedonkin and B. M Waggoner, *Nature* **388**, 868 (1997).
25. C. Nedin and R. J. F. Jenkins, *Alcheringa* **22**, 315 (1998).
26. D. Grazhdankin and M. A. Fedonkin, unpublished data.
27. B. M. Waggoner, *Paleobiology* **25**, 440 (1999).
28. A U-Pb data table and analytical details are presented in Web table 1, which is available at *Science* Online at www.sciencemag.org/feature/data/1047972.
29. A. Seilacher, *Palaios* **14**, 86 (1999).
30. J. G. Gehling, thesis, University of California, Los Angeles (1996), p. 222.
31. D. H. Erwin, *Am. Zool.* **39**, 617 (1999).
32. B. Z. Saylor *et al.*, *J. Sediment. Res.* **68**, 1223 (1998).
33. S. D. Pell *et al.*, *Trans. R. Soc. South Aust.* **117**, 153 (1993).
34. "Broad" is used here in the sense that diverse Ediacarans belonging to taxa found in Australia and Russia could have a range that begins before 555 Ma and extends until after 549 Ma.
35. A. H. Knoll and S. B. Carroll, *Science* **284**, 2129 (1999).
36. X. Xiao, Y. Zhang, A. H. Knoll, *Nature* **391**, 553 (1998).

37. We acknowledge support from NSF (grants EAR97-25727 to S.A.B. and EAR94-18523 to J.L.K. and a graduate research fellowship to D.A.D.E.), the Russian Fund for Basic Research (grant 99-05-64547 to M.A.F.), and the National Geographic Society (grant 6015-97 to M.A.F.). We thank P. Enos, D. Erwin, A. Knoll, W. Hagadorn, B. Hanson, E. Landing, P. Myrow, and one anonymous reviewer for helpful and critical comments on earlier versions of this manuscript. Photographs of Zimnie Gory body and trace fossils were taken by A. Bronnikov.

15 December 1999; accepted 14 March 2000

^{40}K-^{40}Ar Constraints on Recycling Continental Crust into the Mantle

Nicolas Coltice, Francis Albarède, Philippe Gillet

Extraction of potassium into magmas and outgassing of argon during melting constrain the relative amounts of potassium in the crust with respect to those of argon in the atmosphere. No more than 30% of the modern mass of the continents was subducted back into the mantle during Earth's history. It is estimated that 50 to 70% of the subducted sediments are reincorporated into the deep continental crust. A consequence of the limited exchange between the continental crust and the upper mantle is that the chemistry of the upper mantle is driven by exchange of material with the deep mantle.

New continental crust is extracted from the mantle by magmatic processes, whereas old crust is recycled into the mantle at subduction zones. The history of these transfers is not sufficiently understood. In the absence of crustal recycling, a constant rate of about 1.7 km^3 $year^{-1}$ over the entire Earth's history would be required to produce the modern continental crust. Most estimates of the rate of sediment subduction converge at 0.5 to 0.7 km^3 $year^{-1}$ (*1*). When sediment subduction is compounded with mechanical erosion of the crust at subduction zones (*2*), loss of continental crust to the mantle takes place at a rate of 1.6 km^3 $year^{-1}$. The current estimates of addition of mantle material to the crust [1.6 km^3 $year^{-1}$ according to Reymer and Schubert (*3*)], in particular in the form of volcanic products at convergent margins, are therefore inadequate to account for the present mass of the crust unless episodic accretion of large oceanic plateaus is included in the crustal budget (*4*). The modern estimates, however, do not document how crustal growth and recycling have been changing throughout Earth's history. Although the estimates derived from isotopic evolution of Nd in the upper mantle (*5, 6*) look reasonable, they are affected by the unknown extent of material exchange between the upper mantle and the lower mantle. This work considers the constraints on the dual problems of crustal growth and mantle outgassing introduced by the terrestrial inventories of ^{40}K and ^{40}Ar. Although the ^{40}Ar budget of Earth mostly has been used to infer the structure of Earth's mantle (*7*), we show that it also constrains the mean rate of continental recycling.

The coherent model of outgassing and crustal growth (*8*) is introduced first because it is a useful reference. This model assumes that the ^{40}Ar in the continental crust (cc) and in the atmosphere (at) is supported by the ^{40}K inventory of the crustal reservoir. When igneous material is extracted from a particular region of the mantle to form new crust, the ^{40}K of this region is incorporated to the crust and ^{40}Ar is degassed into the atmosphere. Although this model is ideal, it reflects the incompatible character of K during melting and the volatile character of Ar. To assess the deviation of the actual inventory of ^{40}K and ^{40}Ar in the crust and the atmosphere from the coherent model, we define the potential radiogenic argon at time t of a reservoir, hereafter designated $^{40}Ar^{\infty}_{cc+at}$, as the amount of ^{40}Ar that would be present in it after closed-system decay of its current ^{40}K

$$^{40}Ar^{\infty}_{cc+at}(t) = M_{at}(t)\,^{40}Ar_{at}(t) + M_{cc}(t)\,^{40}Ar_{cc}(t) + M_{cc}(t)\,R\,^{40}K_{cc}(t) \quad (1)$$

where $M(t)$ indicates masses, $^{40}Ar(t)$ and $^{40}K(t)$ are concentrations, and R is the proportion of ^{40}K decaying into ^{40}Ar (branching ratio 0.107). For a closed system, $^{40}Ar^{\infty}_{cc+at}$ is a constant. The coherent model for which (i) both Ar and K are extracted from the mantle to the atmosphere and the continental crust, and (ii) there is no degassing at mid-ocean ridges (MORs) or continental recycling requires

Laboratoire des Sciences de la Terre, Ecole Normale Supérieure, 69364 Lyon cedex 7, France.