Calibrating Rates of Early Cambrian Evolution

Samuel A. Bowring, John P. Grotzinger, Clark E. Isachsen, Andrew H. Knoll, Shane M. Pelechaty, Peter Kolosov

An explosive episode of biological diversification occurred near the beginning of the Cambrian period. Evolutionary rates in the Cambrian have been difficult to quantify accurately because of a lack of high-precision ages. Currently, uranium-lead zircon geochronology is the most powerful method for dating rocks of Cambrian age. Uranium-lead zircon data from lower Cambrian rocks located in northeast Siberia indicate that the Cambrian period began at ~544 million years ago and that its oldest (Manykaian) stage lasted no less than 10 million years. Other data indicate that the Tommotian and Atdabanian stages together lasted only 5 to 10 million years. The resulting compression of Early Cambrian time accentuates the rapidity of both the faunal diversification and subsequent Cambrian turnover.

One of the most dramatic events in the fossil record is the explosive diversification of marine invertebrates early in the Cambrian period. Following the appearance of simple, mostly unskeletonized cnidarians, bilaterians, and problematica in uppermost Proterozoic rocks, shelly fossils of Cambrian aspect first appear in carbonate rocks near the base of the Manykay (Nemakit-Daldyn) stage, generally accepted as the basal unit of the Cambrian. During the ensuing Tommotian and Adtabanian stages, animals diversified rapidly, so that by the end of the Adtabanian, most of the extant phyla and classes of marine invertebrates were already in place (*1–3*). The presence of unusual fossils in both conventional skeletal assemblages and Lagerstätten that preserve unmineralized tissues (such as the Burgess Shale) indicates that the diversity of higher taxa was even greater, enriched by groups that failed to survive the period (*4*).

In this article, we report radiometric age determinations on volcanic rocks from northeastern Siberia that place sharp limits on rates of early animal evolution. Obtaining accurate absolute ages historically has been difficult owing to a paucity of suitable rock types and because of the high susceptibility of most rocks and minerals to younger, isotopic resetting. Uranium-lead zircon dating of volcanic rocks interspersed within sedimentary sequences (*5–7*) provides the best prospect for obtaining precise absolute ages for strata about 500 million years or older. The new U-Pb zircon data are from volcanic cobbles that lie beneath basal Tommotian sedimentary rocks of the Kharaulakh Mountains, and from a volcanic breccia intercalated within lower Manykaian strata along the Khorbusuonka River within the Olenek Uplift.

Early Cambrian age estimates. The geological time scale has two components. A chronostratigraphic scale based on a relative sequence of events, predominantly biological, is calibrated in terms of a geochronometric scale based on radiometric ages. The chronostratigraphic basis of the Early Cambrian time scale is well known. By definition, the initial boundary of the period is placed at a point in a stratigraphic section in southeastern Newfoundland, coincident with the first appearance of *Phycodes pedum* and other distinctive traces of animal behavior (*8*). The initial boundary of the earliest Cambrian stage, the Manykaian, is coincident with a transgressive surface at the base of the Manykay Formation in northern Siberia (*9, 10*). The base of the Tommotian stage is marked by a point in a stratigraphic section in southern Siberia (*11*). Calibration requires volcanic rocks suitable for radiometric age determination, and such rocks are not known from the boundary beds of any of these three type sections. Therefore, calibration of the Early Cambrian time scale requires that we identify datable rocks in sections that can be correlated to the type areas by means of bio-, chemo- and magnetostratigraphy.

Recent estimates of the absolute age of the Proterozoic-Cambrian boundary have ranged from 600 to 530 Ma (million years ago) (*12, 13*). The boundary is thought to be younger than the 560 ± 1 million-year-old Ercall granophyre of England (*14*), which is unconformably overlain by Atdabanian strata. In addition, the Mistaken Point Formation of eastern Newfoundland, which contains Ediacaran faunas, has an age of 565 ± 3 Ma (*15*). Odin *et al.* (*12*) suggested that the maximum age of the boundary was between 540 and 520 Ma on the basis of Rb-Sr whole rock ages obtained from basement rocks beneath several lower Cambrian successions. However, the Rb-Sr whole rock method is generally less reliable than U-Pb mineral ages. For example, an Rb-Sr whole rock age of 533 ± 13 Ma on the Ercall granophyre (*16*) is contradicted by the U-Pb zircon age of 560 ± 1 Ma cited above (*14*). The Ercall Rb-Sr age may still be a valid maximum age estimate for the Atdabanian stage if resetting predates deposition above the unconformity (*17*).

The best age estimates for Early Cambrian stage boundaries come from ion-microprobe U-Pb studies of zircons from Lower Cambrian rocks in eastern Canada, Morocco, China, and South Australia (*6, 18*). A minimum age estimate of 545 Ma (no quoted uncertainties) initially was reported (*19*) for a volcanic ash located within the lower Cambrian *Rusophycus avalonesis* zone in southern New Brunswick. However, more recent work (*20*) indicates an age of 531 ± 1 Ma for this ash bed. A volcanic ash interbedded in upper Tommotian sedimentary rocks in Morocco has a mean $^{238}U/^{206}Pb$ age of 521 ± 7 Ma (*6*). In the Meishucun section, China, zircons separated from a bentonite interlayered with rocks estimated to lie near the Tommotian-Atdabanian boundary have a mean $^{238}U/^{206}Pb$ age of 525 ± 7 Ma and a maximum age of 539 ± 34 Ma based on $^{207}Pb/^{206}Pb$ ages (*6*). In South Australia, zircons separated from a volcanic tuff interlayered with latest Atdabanian or Botomian sedimentary rocks have a mean $^{238}U/^{206}Pb$ age of 526 ± 4 Ma (*18*).

In summary, earlier U-Pb zircon studies indicate that the base of the Cambrian is younger than about 560 Ma (*14*) and older than about 525 Ma (*6, 18*). Published estimates for the ages of the Early Cambrian stage boundaries are often contradictory, implying difficulties with analytical or paleontologic control. For example, within the reported analytical errors, one might incorrectly infer that Tommotian-Atdabanian rocks in China (*6*) are younger than Atdabanian-Botomian rocks in South Australia (*18*). Our results reported below provide a direct constraint on the age of the Precambrian-Cambrian boundary and the duration of the oldest Cambrian stage. The dated sections have excellent paleontologic and chemostratigraphic tie points, the ash beds are located close to stage boundaries, and the analytical errors are small.

Cambrian stratigraphic sections in northeast Siberia. *Kharaulakh section.* Basal Cambrian rocks are exposed near the mouth of the Lena River where it crosses the Chekurov anticline. The terminal Proterozoic Kharayutekh Formation and basal

S. A. Bowring, J. P. Grotzinger, C. E. Isachsen, and S. M. Pelechaty are with the Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139. A. H. Knoll is with the Botanical Museum, Harvard University, Cambridge, MA 02138. P. Kolosov is with the Yakutian Geoscience Institute, Yakutsk, Russian Federation.

Cambrian Tyuser Formation, respectively, consist of predominantly carbonate and siliciclastic sedimentary rocks (*21–23*); our measured thicknesses and descriptions are used here. The uppermost Vendian sequence consists of deep-water, finely laminated bituminous limestone that grades upward into shallow-marine ooid-intraclast dolostone about 30 m thick. These carbonate rocks are unconformably overlain by approximately 7 m (Fig. 1) of shallow-marine glauconitic, quartzarenite and siltstone with trough to hummocky cross-stratification. This unconformity is widely accepted as the Proterozoic-Cambrian boundary in this area (*21–23*). The overlying siliciclastic sediments may in part represent basal Cambrian zones 1 to 4 of the Manykay stage (*9, 10*), although no Cambrian faunas have been reported.

Fluvial conglomerate (up to 14 m thick) incises into and unconformably overlies the fine-grained siliciclastic rocks. Compositionally, the conglomerate consists of greater than 99 percent clasts of quartz-feldspar porphyry of volcanic or hypabyssal intrusive origin. The coarse clast size and uniform composition of the conglomerate indicate a proximal source for the clasts. Deposition was probably related to regional high-angle faulting and associated igneous activity (*24*).

The conglomerate is overlain by sandy limestone; a diabase sill intrudes along the contact (Fig. 1). The sandy limestone is about 2 m thick and contains a diverse fauna of small shelly invertebrate fossils (*9, 22*), including *Hyolithellus tenuis* Miss., *H. vladimirovae* Miss., *Torelella* sp., *Coleolus trigonus* Sys., *Lapworthella tortuosa* Miss., *Hertzina*(?) sp., *Tiksitheca korobovi* Miss., *Conotheca mammilata* Miss., *Laratheca nana* Miss., and *Allatheca*(?) *cana* Valk., *Ajacicyathus* ex gr. *khemtschikensis* Zhur., and *Camenella complicata* Mesh. This assemblage indicates an earliest Tommotian age (*9, 10*) and corresponds to the archeocyathid *Aldanocyathus sunniginicus* zone (*25*) and small shelly *Heraultipegma-Lapworthella tortuosa* zone (Cambrian zone 5) (*9, 10*). Consequently, the age of the conglomerate clasts would place a firm maximum on the age of lowermost Tommotian strata.

Khorbusuonka section. The Khorbusuonka section, located within the Olenek Uplift, contains uppermost Vendian strata identical to those in the Kharaulakh section (*9, 10, 26–28*). The section consists of deep-water, finely laminated bituminous limestone (Khatyspyt Formation) that grades upward into shallow-marine ooid-intraclast dolostone (Turkut Formation). A sequence boundary near the top of the Turkut Formation, marked by a karstic surface, defines an uppermost unit of fine oolitic and stromatolitic dolostone. This unit contains the first occurrence of the shelly invertebrate *Cambrotubulus* sp. (*29*). Conventionally, these fossils have been taken to indicate a basal Cambrian age, but, as noted above, the beginning of the Cambrian Period is defined not by shelly fossils but by a point in a stratigraphic column. *Cambrotubulus*-bearing dolostones of the uppermost Turkut Formation correlate chemostratigraphically with rocks that lie immediately beneath the Manykay Stage in the Anabar Uplift of northeastern Siberia and immediately beneath the lowermost occurrences of *Phycodes pedum* in western North America (*28*). The top of this unit is another sequence boundary that marks the contact between the Turkut Formation and overlying Kessyusa Formation.

Basal pebble conglomerate of the Kessyusa Formation is overlain by a few meters of nonfossiliferous siltstone, which is in turn overlain abruptly by a 2- to 15-m-thick volcanic breccia. This breccia was sampled for U-Pb geochronology; it is dominated by pumice and carbonate rock fragments dispersed in a carbonate-rich matrix containing detrital quartz grains and siltstone fragments. This is problematic because such a mixture is prone to the introduction of detrital zircons torn from siliciclastic rock fragments during explosive eruption. This possibility was taken into account during analysis of the zircons.

The breccia is overlain by about 28 m of deep-shelf siltstone, which grades up into shallow-shelf fine sandstone dominated by hummocky cross-stratification. The interval contains a well-defined small shelly invertebrate fossil assemblage including *Anabarites trisulcatus*, *Cambrotubulus sibiricus*, *C. decurvatus*, and *Hyolithellus tschuskunensis*, which characterize the earliest Cambrian *Anabarites trisulcatus* zone (*9, 10*) (Cambrian zone 1). It also contains *Sabellidites cambriensis* and the trace fossil *Phycodes* sp.; siltstones that overlie this unit contain acritarchs that suggest correlation with the Lower Cambrian Lontova horizon of the East European Platform (*30*). Because the breccia is located near the base of the *Anabarites trisulcatus* zone, it provides a direct age constraint on the oldest stage of the Early Cambrian.

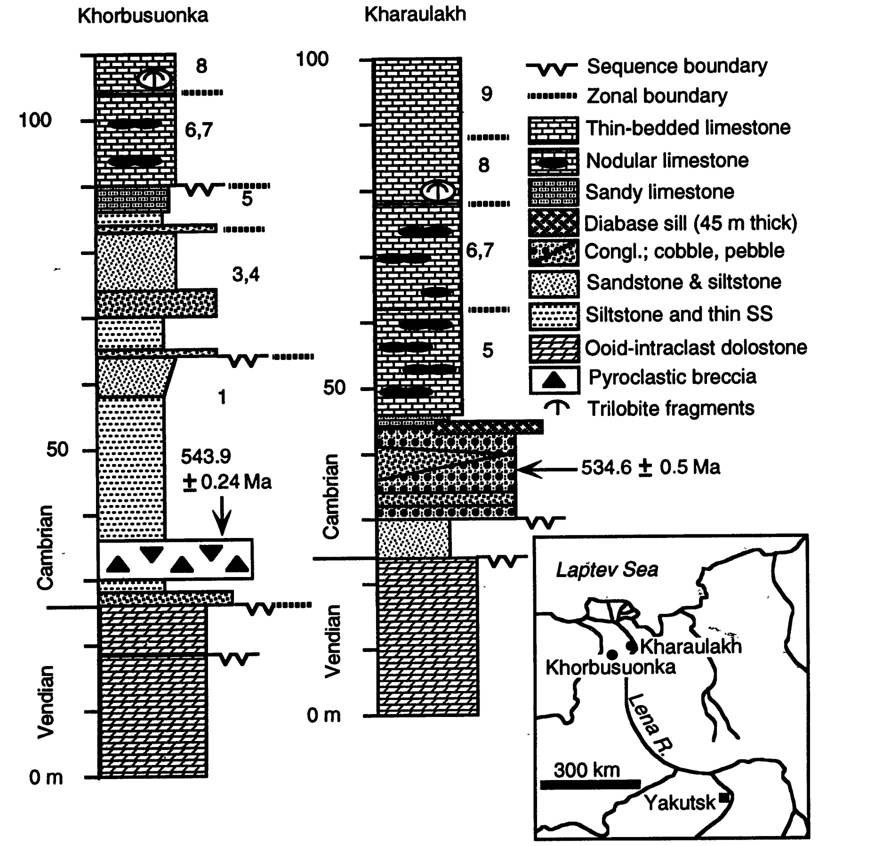

Fig. 1. Measured sections illustrating lithologies, biostratigraphic zonation, and stratigraphic positions of rocks dated in this study. Numbers indicate basal Cambrian fossil zones (*9, 10*): 1–4 (Manykay); 5–7 (Tommotian); 8–9 (Atdabanian). We place the Precambrian-Cambrian boundary (and the base of fossil zone 1) at the Turkut-Kessyusa contact despite sporadic occurrences of *Cambrotubulus* in the upper beds of the Turkut Formation. This assignment has the advantage of defining basal Cambrian strata on the basis of a diverse zone 1 faunal assemblage, as well as honoring chemostratigraphic data that suggest that the uppermost Turkut Formation has a Vendian age (*28*). Inset shows location of sections in northeastern Siberia.

The upper Kessyusa comprises a mixture of pebble conglomerate, siltstone, sandstone, and oolitic and sandy limestone. Fossil assemblages are consistent with an upper Manykay age (*9, 10*) (*Aldanella crassa* and *Anabarella plana* assemblages; Cambrian zones 3 and 4, respectively). The uppermost part of the Kessyusa contains fossils consistent with the basal Tommotian zone (*Heraultipegma-Lapworthella tortuosa* assemblage; Cambrian zone 5).

Uranium-lead dating. Using the U-Pb method, it is possible to exploit two independent decay schemes ($^{238}U/^{206}Pb$ and $^{235}U/^{207}Pb$) in each zircon sample to provide independent age information and to serve as a test for the degree to which closed system behavior has been adhered to subsequent to crystallization. Zircons are resistant to resetting caused by younger thermal overprints. Two methods of U-Pb zircon analysis have been applied in the last few years: conventional isotope dilution thermal ionization mass spectrometry (IDTIMS) and the sensitive high-resolution ion microprobe (SHRIMP).

With IDTIMS, the method we used (*32*), it is now routinely possible to analyze 50 to 250 pg of radiogenic Pb with analytical blanks of 1 to 4 pg (*7*). Zircons are separated from volcanic rocks, categorized according to shape, size, color, presence of inclusions, clarity, and magnetic susceptibility, air-abraded, and dissolved in HF. In general, the clearest, crack- and inclusion-free, and least magnetic zircons contain the lowest concentrations of U and are most likely to yield concordant results. Zircons of early Paleozoic age typically have radiogenic lead concentrations between 5 and 20 ppm. At a concentration of 10 ppm, analysis of 100 to 200 pg of Pb would require 10 to 20 μg of zircon. For dating most Cambrian volcanic rocks, anywhere from 1 to 20 zircons, depending on their size, is required.

When a zircon or group of zircons has remained a closed system since crystallization, the $^{206}Pb/^{238}U$, $^{207}Pb/^{235}U$, and $^{207}Pb/^{206}Pb$ ages are equal within uncertainties. If some of the radiogenic Pb has been lost from the zircons, perhaps because of radiation damage, a discordant array of ages results where the $^{207}Pb/^{206}Pb$ age > $^{207}Pb/^{235}U$ age > $^{206}Pb/^{238}U$ age. The discordant data commonly define a linear array, and the intersection of the array with the concordia curve is used as an estimate of the crystallization age of the zircons. Alternatively, if some of the zircons or even cores of zircons are inherited from older rocks, as is common in volcanic rocks erupted through continental crust, older ages will result. Further complexity can be involved when inheritance and Pb loss are combined; high-precision isotopic analyses are required to distinguish these effects. IDTIMS of 50 to 500 pg of Pb and U typically lead to two-sigma uncertainties in parent:daughter ratios of 0.5 to 0.2 percent, and of 0.3 to 0.1 percent in the $^{207}Pb/^{206}Pb$ ratio. A problem involved with analyzing multiple grains is that a single grain of older zircon that was incorporated during volcanic eruption or deposition may subtly skew the results when included with a number of other magmatic grains. Ideally, single grains should be analyzed and, if not possible because of low radiogenic Pb contents, then multiple analyses of multigrain fractions should be attempted to evaluate fully the coupled effects of Pb loss and inheritance (*7*).

Some of these problems can be overcome using the SHRIMP ion microprobe (*31*). Unlike the conventional approach, the ion microprobe is capable of analyzing small domains within single zircon crystals for their U and Pb isotopic compositions, without the complications of correcting for common Pb associated with analytical blanks. However, the dramatically improved spatial resolution comes at the expense of analytical precision; one-sigma

Table 1. Uranium-lead isotopic data. Zircon fractions are designated as magnetic (m) nonmagnetic (nm), and diamagnetic (d) in terms of degrees tilt on a Frantz LB-1 magnetic separator. The number of grains in each fraction is shown in parentheses. Sample weights, estimated using a video monitor with a gridded screen, are known to within 10%.

Fractions	Weight (μg)	U (ppm)	Pb* (ppm)	Total common Pb (pg)	Atomic ratios								Ages (Ma)		
					^{206}Pb† / ^{204}Pb	^{208}Pb‡ / ^{206}Pb	^{206}Pb‡ / ^{238}U	% err	^{207}Pb‡ / ^{235}U	% err	^{207}Pb / ^{206}Pb‡	% err	^{206}Pb / ^{238}U	^{207}Pb / ^{235}U	^{207}Pb / ^{206}Pb
									Kharaulakh						
K-TU-2 #2															
d-1(4)	24	101.4	9.0	11.9	1151	0.142	0.08599	0.26	0.68906	0.29	0.05812	0.12	531.8	532.2	534.2
d-1(1)	10	75.6	6.8	6.1	756	0.143	0.08667	0.78	0.69483	0.80	0.05814	0.17	535.8	535.7	535.1
d-1(2)	11	88.8	8.0	6.3	855	0.143	0.08670	0.65	0.69495	0.66	0.05814	0.13	536.0	535.8	534.9
d-1(1)	19	194.2	17.8	12.1	1640	0.172	0.08647	0.17	0.69342	0.20	0.05816	0.11	534.7	534.9	535.7
K-TU-2 #7															
m10(6)	25	191.6	17.3	16.0	1642	0.157	0.08622	0.21	0.69092	0.26	0.05812	0.15	533.2	533.4	534.1
d-1(4)	12	78.4	7.0	7.8	663	0.146	0.08620	0.67	0.69074	0.70	0.05811	0.17	533.0	533.2	534.1
m3(18)	80	170.6	15.2	9.6	7631	0.143	0.08646	0.18	0.69278	0.18	0.05812	0.05	534.5	534.5	534.2
d-1(12)	10	188.4	16.8	4.0	2581	0.139	0.08642	0.33	0.69270	0.34	0.05814	0.08	534.3	534.4	534.9
m3(14)	79	114.1	10.2	11.3	4328	0.150	0.08637	0.14	0.69217	0.17	0.05812	0.10	534.0	534.1	534.4
									Khorbusuonka						
d-1(1)	6	64.2	5.9	4.1	582	0.168	0.08781	0.63	0.70631	0.80	0.05834	0.47	542.6	542.6	542.5
nm5(1)	10	118.8	11.1	5.5	1238	0.176	0.08786	0.53	0.70714	0.61	0.05837	0.28	542.9	543.0	543.6
m2(4)	22	172.5	15.6	13.0	1636	0.140	0.08766	0.14	0.70548	0.18	0.05837	0.10	541.7	542.1	543.7
m2(5)	21	163.4	14.8	7.5	2546	0.145	0.08762	0.18	0.70521	0.21	0.05837	0.10	541.5	541.9	543.7
m4(5)	25	115.2	10.9	7.8	2069	0.195	0.08785	0.30	0.70712	0.32	0.05838	0.10	542.8	543.0	544.1
m2(21)	39	144.8	13.2	14.2	2182	0.159	0.08703	0.13	0.70056	0.15	0.05838	0.08	538.0	539.1	544.1
d-1(21)	25	103.4	9.4	9.3	1564	0.161	0.08708	0.29	0.70100	0.34	0.05839	0.19	538.2	539.4	544.2
m2(11)	11	491.1	48.7	9.1	3400	0.202	0.09122	0.13	0.76856	0.15	0.06111	0.07	562.7	578.9	643.0
m2(11)	30	116.9	30.8	8.8	5330	0.213	0.23088	0.10	3.56569	0.12	0.11201	0.07	1339.1	1541.9	1832.2
m2(9)	20	125.5	56.7	10.9	5134	0.206	0.38856	0.09	7.77863	0.10	0.14519	0.04	2116.2	2205.7	2290.0
m2(3)	16	180.6	79.4	39.8	1624	0.155	0.39029	0.09	8.27346	0.11	0.15374	0.06	2124.2	2261.4	2387.9

*Radiogenic Pb. †Measured ratio corrected for fractionation only; Pb fractionation correction is 0.1% ± 0.03% per atomic mass unit. ‡Corrected for fractionation, spike, blank, and initial common Pb; U blank = 1 pg ± 50%; Pb blank = 3.5 pg ± 50%. Initial common Pb composition is calculated from Stacey and Kramers (*42*) with the interpreted age of the sample. Errors are reported in percent at the two-sigma confidence interval.

errors for individual analyses are typically 2 to 3, 5 to 6, and 3 to 5 percent for $^{206}Pb/^{238}U$, $^{207}Pb/^{235}U$, and $^{207}Pb/^{206}Pb$, respectively, for Cambrian age volcanic zircons (*6, 18*). Such imprecision makes the detection of subtle effects of Pb loss and inheritance difficult to assess. In general, the $^{206}Pb/^{238}U$ age is regarded as the most precise SHRIMP determination for this age interval. Age is generally estimated by calculating a weighted mean of the $^{206}Pb/^{238}U$ determinations from 20 to 50 individual analyses. Underlying this approach is the assumption that the small diameter of the ion beam can be used to select the parts of single grains that yield concordant ages.

Kharaulakh section. Two cobbles, each about 20 cm in diameter (K-TU-2 #7 and #2), were removed from the outcrop of conglomerate and processed separately. The cobbles contain abundant zircons, which are typically pink, stubby, doubly terminated, and inclusion-rich. The most common inclusions are opaque minerals and apatite. The zircons range in size from 50 to 200 mm, which correspond to approximate weights of >1 to 10 μg per zircon. Zircons were analyzed (data for nine analyses are in Table 1) both as single grains and as carefully selected small populations, to evaluate heterogeneity in terms of Pb loss and inheritance. Most of these analyses involved 100 to 300 pg of total Pb.

Many of the analyses were nearly concordant (Fig. 2A). The data form a linear array that clusters along the concordia curve. There are at least two ways that the data can be evaluated: (i) all of the analyses cluster near concordia with mean $^{206}Pb/^{238}U$, $^{207}Pb/^{235}U$, and $^{207}Pb/^{206}Pb$ ages and errors (95 percent confidence limit) of 534.0 ± 0.9 Ma, 534.1 ± 0.8 Ma, and 534.6 ± 0.4 Ma, respectively. If the scatter in the nine nearly concordant data points is caused only by uncertainties in isotopic measurements and all points are concordant, the mean of the three ages is 534.2 ± 0.4 Ma. Alternatively, (ii) the slight difference between the three mean ages could be viewed as the result of Pb loss. In this case the weighted mean of the $^{207}Pb/^{206}Pb$ ages (534.6 ± 0.4 Ma) is the best estimate of the age of the boulders and the best estimate for the maximum age of the basal Tommotian.

Khorbusuonka section. We separated zircons from a 10-kg sample of volcanic breccia. The breccia is characterized by large aphanitic fragments of iron-rich, pumiceous volcanic rocks and abundant dolomite and argillite rock fragments. The volcanic fragments contain microlites of sanidine, many of which exhibit swallowtail structures. We interpret the breccia to be the product of a phreatomagmatic eruption. Zircons separated from the breccia range from euhedral, doubly terminated, yellowish, clear crystals to large, rounded, and frosted grains. About 10 percent are clear and have sharp terminations and no evidence of frosting. All of the latter grains contain small inclusions of rutile and apatite. We abraded and analyzed seven fractions of these zircons. The grains are typically small (100 μm) and characterized by low Pb concentrations (15 ppm), requiring analysis of multiple grains. Five multiple grain and two single grain analyses yield consistent results, including three points that are essentially concordant (Fig. 2B and Table 1). However, all of the analyses show a typical discordance with the $^{206}Pb/^{238}U$ age < $^{207}Pb/^{235}U$ age < $^{207}Pb/^{206}Pb$ age. As the sample contains abundant rounded detrital grains it is possible that a multigrain population may contain one or more of the older zircons, which could slightly skew the results toward an older age. Thus, two single grains of the euhedral, inclusion-bearing suite were analyzed. The smallest single grain contained only 35 pg of total Pb with 4 pg of total (sample plus blank) common Pb, and thus has a correspondingly large error ellipse. The other single grain contained 113 pg of total Pb with 5.5 pg of total common Pb. However, both grains are essentially concordant and are identical in age to the five multigrain fractions. These data confirm that the component zircons in the multigrain populations are of one age. Regression of all seven analyses yields an upper intercept age of 543.8 + 5.1/−1.3 Ma, a lower intercept of −25 ± 367 Ma, and a MSWD of 0.03. As the lower intercept is essentially 0 Ma, the best estimate of the age of the

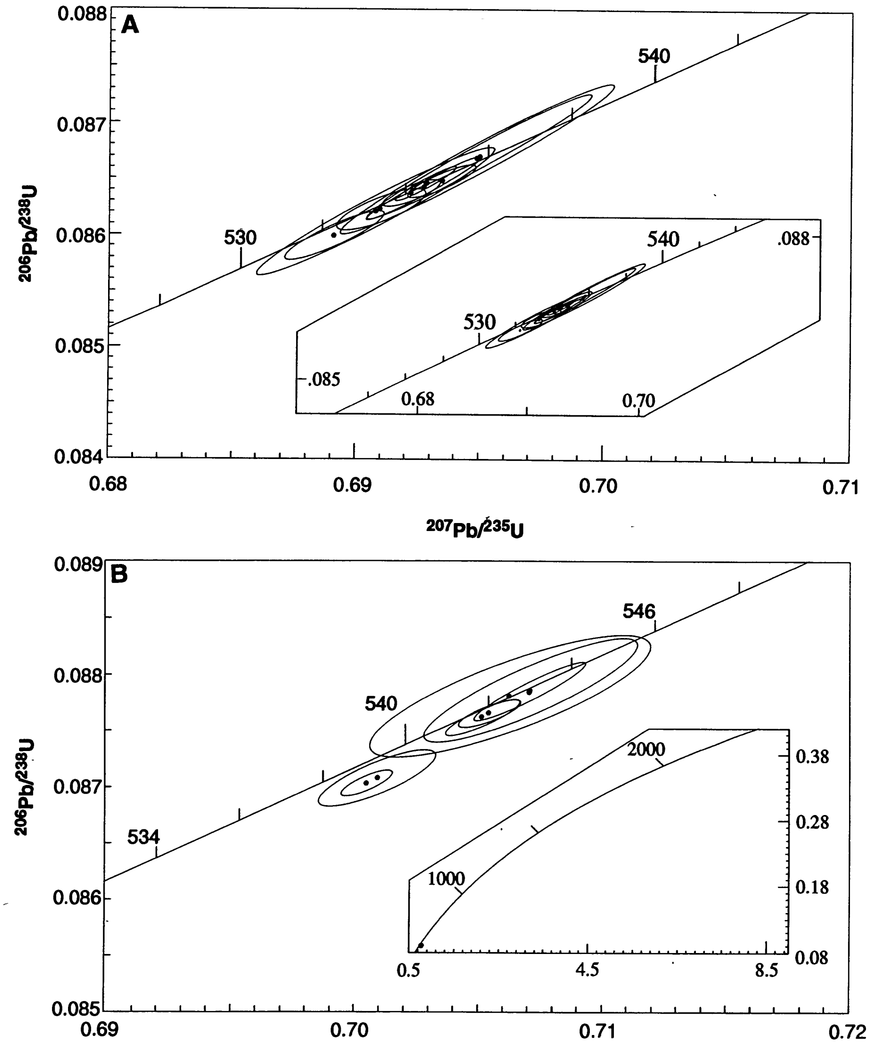

Fig. 2. (**A**) Concordia diagram for Kharaulakh zircons. Ages, in millions of years ago, are marked on the concordia curve. Individual analyses are depicted as 2σ error ellipses. Inset shows the same data and error ellipses plotted at a reduced scale but circumscribed (inset outline) by a representative one-sigma SHRIMP error polygon (*18*) for a single analysis of ~500-million-year-old zircons; this polygon encloses all of the two-sigma ellipses from this study. (**B**) Concordia diagram for zircons from the Khorbusuonka volcanic breccia. Ages are marked on the concordia curve. Inset shows concordia curve with analyses of detrital zircons from breccia.

breccia is the weighted mean of the $^{207}Pb/^{206}Pb$ ages of the seven analyses. This yields an age of 543.9 ± 0.2 Ma that is identical to the regression but with a lower uncertainty.

We also analyzed four multigrain fractions of obviously rounded grains, which ranged from yellow to dark brown. These zircons have much older ages and suggest that they are detrital grains, derived from underlying Vendian sandstone and siltstone, which in turn were derived from erosion of underlying crystalline basement. The $^{207}Pb/^{206}Pb$ ages range from 643 Ma to 2388 Ma and may reflect mixing among zircons of Cambrian, Paleoproterozoic and Archean ages. The multigrain fraction that yielded the 643 Ma Pb-Pb age probably contains several grains from the volcanic component, which may have been slightly rounded during the eruption and deposition of the breccia. We interpret the age of 543.9 ± 0.2 Ma to be the age of the volcanic component and therefore a maximum age for the breccia.

Calibration of Early Cambrian evolutionary rates. Calibration of the Early Cambrian time scale, with the use of high-precision U-Pb ages from volcanic rocks interstratified with Early Cambrian fossils, has important implications for our understanding of the Cambrian explosion and its immediate aftermath. Although uncertainties remain in the precise correlation of the breccia to the initial Cambrian boundary stratotype in Newfoundland, we estimate that the age of the Proterozoic-Cambrian boundary is 544 Ma. We suggest a maximum age of 533 Ma for the Manykaian-Tommotian boundary (the horizon commonly taken as the Precambrian-Cambrian boundary in literature published before 1990). This interpretation is reinforced by recent results from New Brunswick (*20*), which suggest an age of 531 Ma for upper Manykaian strata. These two results together suggest that the age of the Manykaian-Tommotian boundary is approximately 530 Ma.

Full characterization of evolutionary rates requires calibration of younger Early Cambrian ages as well. However, this is more difficult because of overlapping age determinations. Of three recent analyses (*6, 18*), we regard the age determination of the latest Atdabanian-Botomian strata from South Australia, on the basis of geochronologic and paleontologic control, as the most relevant to dating the younger Early Cambrian ages. We infer that the Atdabanian-Botomian boundary has an age of ~525 Ma. The age of the Cambrian-Ordovician boundary is poorly constrained, but if one accepts the ages of 510 to 505 Ma in most compilations (*33*), then more than half of all Cambrian time is taken up by the first three ages of the Early Cambrian (Fig. 3).

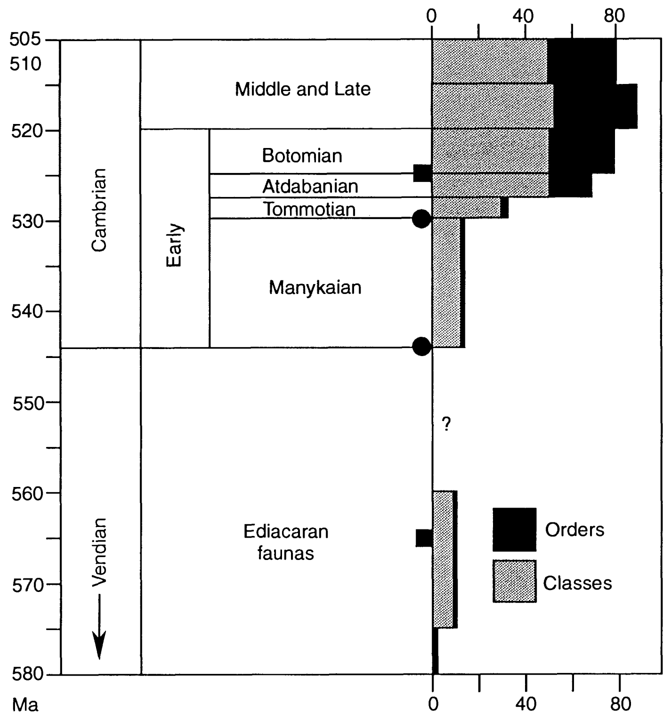

Fig. 3. A revised time scale for the Cambrian period. Boundaries that are well constrained by U-Pb zircon geochronology are marked by filled circles (this article) or filled squares (other data referenced in the text). Ages for other boundaries are poorly constrained. In some treatments, the upper part of the Botomian age is segregated as the Toyonian age. Diversity data from Sepkoski (*2*).

Analyses of the Cambrian faunal radiation indicate that diversification followed a logistic pattern of increase (*1, 2, 34, 35*). Our calibration shows that the initial (Manykaian) interval of slow diversification followed the ediacaran faunal epoch by no more than 20 million years (m.y.) and lasted approximately 14 m.y. In contrast, if we accept the age of 525 Ma for the Atdabanian-Botomian boundary, then the Tommotian-Atdabanian period of exponential increase of diversification lasted only 5 to 6 m.y. In any event it is unlikely to have exceeded 10 m.y. Numbers of phyla, classes, orders, families, and genera all reached or approached their Cambrian peaks during the short Tommotian-Atdabanian interval (*1–3, 34, 35*). For phyla and classes, most of the diversity known for the Phanerozoic as a whole differentiated by the end of the Atdabanian. Indeed, by some accounts (*4*) the number of Early to Middle Cambrian phyla exceeded that known today. [The exceptionally preserved fossils of the Middle Cambrian Burgess Shale complicate this picture, but we concur with Valentine *et al.* (*3*) that most higher taxa present in the Burgess fauna originated during the early Cambrian.]

This increase in the taxonomic richness of fossil invertebrates is matched by a sharp contemporaneous increase in the diversity of trace fossils (*36*) and the intensity of bioturbation (*37*), providing an independent indicator of rapid animal evolution. Planktonic algae show a comparable pattern of early Cambrian diversification (*38*), and together, these developments indicate a broad enrichment of the biota. It has long been inferred that the Cambrian explosion was fast; now we have some idea of just what fast means.

While radiometric calibration has consequences for considerations of the early Cambrian explosion, there are also implications for how later Cambrian evolution is viewed. If we accept that the Tremadocian epoch (taken as the beginning of the Ordovician Period in Europe, but postdating the traditionally recognized Cambrian-Ordovician boundary in North America) began 505 to 510 Ma, then the Middle to Late Cambrian diversity plateau recognized by Sepkoski (*1, 2, 34, 35*) shrinks to a short respite before renewed Ordovician diversification. Evolutionary turnover among trilobites, long known to have been rapid, turns out to be among the fastest observed in the Phanerozoic record. Foote (*39*) estimated that median generic longevity for Cambrian trilobites was about 2.1 m.y., compared with 6.3 m.y. for Ordovician trilobites and 10.6 for Phanerozoic invertebrates as a whole (*40*). In the revised time scale, median Cambrian generic longevity shrinks to just over 1 m.y., whereas the median longevity for Cambrian trilobite species becomes ~750,000 years [recalculated (*39*)]. This increases the disparity observed by Foote (*39*) between Cambrian and Ordovician trilobite longevities, and underscores the remarkable biostratigraphic resolution of Middle and Late Cambrian trilobite zones (*41*).

These diversification rates likely will have to be modified as better age constraints are obtained. Quantifying rates of geologic and biologic processes is ultimately dependent on precise geochronology and chronostratigraphy. The principal uncertainty in our analysis is the numeric ages derived from the younger rather than older end of the Cambrian scale, even though the chronostratigraphy is more precise there. Although poorly calibrated in the past, continued application of the U-Pb zircon method promises to establish the Cambrian time scale with a level of accuracy rivaling, and perhaps exceeding, that of the younger Paleozoic Era.

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32. The U-Pb isotopic data were acquired in the radiogenic isotope lab at the Massachusetts Institute of Technology. These are the first zircon data reported from this lab. Zircons were separated from the three samples with the use of standard techniques of crushing, Wilfley table, magnetic separation, and heavy liquids. Zircons for analysis were then selected on the basis of size, color, and the lack of inclusions. The selected zircons were then air-abraded [T. E. Krogh, *Geochim. Cosmochim. Acta.* **45**, 637 (1982)] to remove the outer portion of the grains and acid washed in warm 4N HNO_3 for one-half hour before dissolution in HF + HNO_3. The zircons were spiked with a mixed ^{205}Pb-^{233}U-^{235}U tracer solution before dissolution in Teflon bombs at 220°C for 48 hours. Lead and uranium were separated from the resulting solution using anion exchange chemistry [T. E. Krogh, *ibid.* **37**, 488 (1973)]. Total procedural blanks during the course of these analyses were 2.0 to 3.5 pg for Pb and less than 1 pg for U. Total common Pb is reported for each analysis in Table 1. Lead was loaded on single rhenium filaments with silica gel and phosphoric acid. Isotopes of Pb were measured with a VG Sector-54 thermal ionization mass spectrometer using a Daly detector in ion-counting mode. In general an ion-beam between 0.5 and 1.5 × 10^{-13} A was maintained for ^{206}Pb during data acquisition. Uranium was loaded with phosphoric acid and colloidal graphite on rhenium filaments and was measured as metal ions in static mode by utilizing three Faraday collectors and an average ^{235}U ion beam intensity of 2.5 × 10^{-13} A. Errors in the $^{238}U/^{206}Pb$, $^{235}U/^{207}Pb$, and $^{207}Pb/^{206}Pb$ were estimated using the method of K. R. Ludwig [*U.S. Geol. Surv. Open File Rep. 88-557* (1988)], and all age uncertainties are quoted at the two-sigma confidence level. Additional analytical details are presented in Table 1.
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