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.

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

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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

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$$\frac{{}^{40}\mathrm{Ar}^{\infty}_{\mathrm{cc+at}}(t)}{M_{\mathrm{cc}}(t)\,R\,{}^{40}\mathrm{K}_{\mathrm{cc}}(t)} = e^{\lambda t} \qquad (2)$$

where λ is the total decay constant of ^{40}K (5.543×10^{-10} year^{-1}). The $^{40}\mathrm{Ar}^{\infty}_{\mathrm{cc+at}}$ is therefore conserved upon radioactive decay and coherent crustal growth but not through outgassing or crustal recycling.

Evidence that degassing occurs at MORs (*9*) and that crustal sediments are recycled into the mantle (*1*) suggests that assumption (ii) of the coherent model is incorrect. Assumption (i), in contrast, is acceptable because K and Ar are very incompatible (*10*). Therefore, we define the excess parameter $^{40}\mathrm{Ar}^{\mathrm{xs}}_{\mathrm{cc+at}}$ as the amount of ^{40}Ar in the system cc + at unsupported by ^{40}K and therefore due to degassing and/or recycling with respect to the coherent model

$$^{40}\mathrm{Ar}^{\mathrm{xs}}_{\mathrm{cc+at}}(t) = {}^{40}\mathrm{Ar}^{\infty}_{\mathrm{cc+at}}(t) - M_{\mathrm{cc}}(t)\,R\,{}^{40}\mathrm{K}_{\mathrm{cc}}(t)e^{\lambda t} \qquad (3)$$

where the first term on the right is from Eq. 1. The corresponding excess age T^{xs} is

$$T^{\mathrm{xs}} = \frac{1}{\lambda}\, ln\left[\frac{{}^{40}\mathrm{Ar}^{\infty}_{\mathrm{cc+at}}(t)}{M_{\mathrm{cc}}(t)R\,{}^{40}\mathrm{K}_{\mathrm{cc}}(t)}\right] - t \qquad (4)$$

The modern volume of continental crust estimated from two different geophysical models is 7.8×10^9 km^3 (*11*). We use a time-invariant K content of the continental crust of 1.6 weight percent (*12*) and this assumption is evaluated below. The mass of ^{40}K hosted in the continental crust is therefore 4.5×10^{16} kg. The amount of radiogenic ^{40}Ar in the atmosphere is about 6.6×10^{16} kg (*12*). As geologically plausible values, we assume that the continental crust has a mean age of 2.7×10^9 years (Gy) and lost 50% of its radiogenic argon; therefore it is home to 0.59×10^{16} kg of ^{40}Ar. Because the atmosphere is devoid of K and is the dominant reservoir of ^{40}Ar, the resulting values of $^{40}\mathrm{Ar}^{\mathrm{xs}}_{\mathrm{cc+at}} = 1.9 \times 10^{16}$ kg, and $T^{\mathrm{xs}} = 463 \times 10^6$ years are nearly insensitive to the age of the continental crust and its extent of degassing. The implication of this calculation is that <30% of the radiogenic ^{40}Ar in the atmosphere and the continental crust is unsupported.

If the crustal concentration of Rudnick and Fountain (*13*) is replaced by higher estimates (*14*, *15*), the unsupported ^{40}Ar decreases. For the extreme 2.0 wt% K value of Wedepohl (*15*), it becomes essentially zero. In contrast, the lower K value of Taylor and McLennan (*16*) (0.9 wt% K) doubles the excess Ar. Such a value, however, reduces the predicted radioactive heat production in the continental crust to about one-third of the surface heat flow, which is too low with respect to our current understanding of the heat flow at the base of the crust (*17*). Secular variations of the chemical composition of the crust outside the range observed for the modern crustal segments is unsupported (*16*); therefore, we consider the ^{40}K estimate provided by (*13*) to be adequate.

As heating and outgassing upon subduction prevent significant Ar recycling in the mantle, the excess Ar provides strong constraints on the rate of crustal recycling and mantle outgassing. Taking the derivative of Eq. 3 with respect to *t*, we get

$$\frac{d\,{}^{40}\mathrm{Ar}^{\infty}_{\mathrm{cc+at}}}{dt} = \frac{d[M_{\mathrm{at}}\,{}^{40}\mathrm{Ar}_{\mathrm{at}}]}{dt} + \frac{dM_{\mathrm{cc}}}{dt}R\,{}^{40}\mathrm{K}_{\mathrm{cc}}(1 - e^{\lambda t}) + \lambda M_{\mathrm{cc}}R\,{}^{40}\mathrm{K}_{\mathrm{cc}}(1 - e^{\lambda t}) \qquad (5)$$

which shows that production $^{40}\mathrm{Ar}^{\mathrm{xs}}_{\mathrm{cc+at}}$ depends only on the outgassing flux of ^{40}Ar and on evolution of the crustal mass through time. The quantity $^{40}\mathrm{Ar}^{\mathrm{xs}}_{\mathrm{cc+at}}$ can be ascribed to either degassing of ^{40}Ar, presumably at MORs and hot spots, to recycling of K from the crust (continental and oceanic) into the mantle, or to any combination of either process. Because heating and outgassing upon subduction prevent significant Ar recycling in the mantle, reinjection of terrigenous sediments and subduction of outgassed basaltic material increase $^{40}\mathrm{Ar}^{\mathrm{xs}}_{\mathrm{cc+at}}$ and incorporation of material extracted from a degassed mantle reduces it.

An extreme interpretation would hold that (i) subduction of crustal K is negligible and (ii) mantle degassing at MORs and hot spots is more efficient than extraction of K from the oceanic lithosphere into continental crust, a situation that leads to positive $^{40}\mathrm{Ar}^{\mathrm{xs}}_{\mathrm{cc+at}}$. The corresponding ^{40}Ar flux averaged over 4.5 Gy is about 4.2×10^6 kg year^{-1}. This represents <50% of the ^{40}Ar radioactive ingrowth for a primitive mantle the size of the modern mantle and crust together (*18*). This flux is larger than current estimates of the modern flux of ^{40}Ar at the surface of the Earth by a factor of 2 to 7 (*9*). Because ^{40}Ar/^{36}Ar in the mantle is at least 150 times higher than that in the atmosphere (*19*), large amounts of Ar must have actually been released into the atmosphere before significant radiogenic ingrowth of ^{40}Ar occurred. Current estimates of the age of atmospheric rare gases are about 4.4 Gy (*20*). Because extraction of the continental protolith involves extraction of both K and Ar from the mantle and in view of the value of $^{40}\mathrm{Ar}^{\mathrm{xs}}_{\mathrm{cc+at}}$, crustal formation also must have started very early in Earth's history.

In the opposite case, extraction of ^{40}Ar and ^{40}K from the mantle into the mantle-crust system remains coherent in the sense of (*8*) and $^{40}\mathrm{Ar}^{\mathrm{xs}}_{\mathrm{cc+at}}$ reflects only recycling of terrigenous sediments into the mantle and delamination of the lower continental crust. Then $^{40}\mathrm{Ar}^{\mathrm{xs}}_{\mathrm{cc+at}}$ builds up at the rate given by

$$\frac{d\,{}^{40}\mathrm{Ar}^{\mathrm{xs}}_{\mathrm{cc+at}}}{dt} = F(t)\,{}^{40}\mathrm{K}_{\mathrm{cc}}(0)\,R(1 - e^{-\lambda t}) \qquad (6)$$

where F is the mass flux of recycled crust. Integration of Eq. 6 for time-invariant F leads to

$$F = {}^{40}\mathrm{Ar}^{\mathrm{xs}}_{\mathrm{cc+at}} \Big/ \left\{ {}^{40}\mathrm{K}_{\mathrm{cc}}(0)R\left[T + \frac{1}{\lambda}(e^{\lambda T} - 1)\right]\right\} \qquad (7)$$

so that F is 2.7×10^{12} kg year^{-1} (about 1.0 km^3 year^{-1}). We have tried to vary the shape of the function $F(t)$, but the value for a time-invariant F remains an upper bound for the modern recycling rate. F is lower than the present-day rate of crustal formation of $\sim 6 \times 10^{12}$ kg year^{-1} deduced from geochemistry (*3*, *4*) or geological inventory (*5*, *6*).

The $^{40}\mathrm{Ar}^{\mathrm{xs}}_{\mathrm{cc+at}}$ is actually an upper bound for recycling crustal ^{40}K and for outgassing ^{40}Ar. Production of $^{40}\mathrm{Ar}^{\mathrm{xs}}_{\mathrm{cc+at}}$ is therefore to be distributed between recycling and outgassing, which makes the maximum value of 1.0 km^3 year^{-1} established above a quite conservative maximum value of the actual rate of crustal recycling. Models of Nd isotope secular evolutions suggest that continental crust is lost to the mantle at a rate of 0.8 ± 0.5 km^3 year^{-1} (*6*) to 2.5 km^3 year^{-1} (*5*). Geometric evaluation of sediment loss to subduction zones is consistent with values of 0.5 to 0.7 km^3 year^{-1} (*1*), a value that subduction erosion at convergent margins increases to 1.6 km^3 year^{-1} (*2*).

The contribution of MORs and hot spots to atmospheric Ar, in particular the superplumes for which the rare gas fluxes are particularly difficult to estimate, would further reduce the rate of recycling. The modern ^{40}Ar flux estimated by Allègre *et al.* (*7*) corresponds to 6 to 50% of the average production rate of $^{40}\mathrm{Ar}^{\mathrm{xs}}_{\mathrm{cc+at}}$. Depending on how ^{40}Ar outgassing is compensated by ^{40}K extraction into the continental crust, the mean rate at which crustal material has been entrained into the mantle by subduction zones may be as low as 0.5 km^3 year^{-1}. If the rate of recycling has remained approximately constant over Earth's history, the discrepancy between the present estimate and those produced by other methods suggests that 30 to 70% of the crustal material that appears to disappear into subduction zones is actually reincorporated into the continental lithosphere either as magmatic products or into the lower crust as metamorphic material.

The surprisingly small fraction of the continental mass lost to the mantle (≤30%) and the corresponding small rates of continental recycling inferred from the ^{40}Ar budget appear to conflict with the evidence from the Sm/Nd isotopic evolution of the mantle-crust system. DePaolo (*5*) pointed out that the apparent ^{147}Sm/^{144}Nd ratios deduced from secular evolution of the ^{143}Nd/^{144}Nd ratios in material derived from the upper mantle (0.21) and from the continental crust (0.15) are significantly different from those actually observed in the source rocks of this material (0.25 and 0.12, respectively). The recycling rate inferred from the $F(t)$ constraint is too small to explain the discrepancy between the observed and inferred Sm/Nd ratios in each reservoir. Therefore, Nd isotopic evolution of the upper mantle is controlled not only by recycling of continental crust but also by exchange of material with a different reservoir (*21*) with a low $^{147}Sm/^{144}Nd$ ratio, which could be material segregated from subducted lithospheric plates (*22*) or a deep layer left behind by early terrestrial differentiation (*23*).

These constraints from the ^{40}Ar budget of the observable reservoirs depend on the very incompatible behavior of K and Ar and therefore are robust. Only if Ar were substantially more compatible than K would the conclusions be clearly inadequate. The solubility of Ar in olivine melt actually may decrease dramatically beyond 4 to 5 GPa (*24*). Partial melting possibly extended at 150 to 200 km in the past because the mantle was hotter, especially under the MORs. So far, however, the compatible behavior of ^{40}Ar during melting remains to be demonstrated and the constraints on the rate of continental growth and mantle degassing given by the ^{40}Ar and K budget remain.

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Satellite Measurements of Sea Surface Temperature Through Clouds

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Measurements of sea surface temperature (SST) can be made by satellite microwave radiometry in all weather conditions except rain. Microwaves penetrate clouds with little attenuation, giving an uninterrupted view of the ocean surface. This is a distinct advantage over infrared measurements of SST, which are obstructed by clouds. Comparisons with ocean buoys show a root mean square difference of about 0.6°C, which is partly due to the satellite-buoy spatial-temporal sampling mismatch and the difference between the ocean skin temperature and bulk temperature. Microwave SST retrievals provide insights in a number of areas, including tropical instability waves, marine boundary layer dynamics, and the prediction of hurricane intensity.

The surface temperature of the world's oceans plays a fundamental role in the exchange of energy, momentum, and moisture between the ocean and the atmosphere. It is a central determinant of air-sea interactions and climate variability. The recurring El Niño–La Niña cycle, which has a profound effect on the world's weather and climate, is a dramatic manifestation of the coupling of SST to atmospheric circulation (*1*, *2*). The surface temperature field also influences the development and evolution of tropical storms and hurricanes (*3*, *4*) and is correlated with nutrient concentration and primary productivity (*5*).

Satellite measurements of SST began in the 1970s, using infrared radiometers flying aboard the National Oceanic and Atmospheric Administration's geostationary and polar orbiting platforms (*6*). Satellite infrared SST measurements have resulted in major advancements in oceanography, meteorology, and climatology (*2*, *7–10*). However, the infrared SST retrievals have two significant limitations: (i) Retrievals cannot be done when clouds (which cover roughly half the Earth) are present. (ii) Atmospheric aerosols from volcanoes and large fires can cause a spurious cooling in the SST retrieval (*11*, *12*). The aerosol problem has been particularly troublesome when trying to construct multiyear time series to infer climate change (*11*). Furthermore, the cloud detection algorithms are not totally reliable, with some clouds going undetected.

It has long been recognized that microwave radiometry offers a solution to the cloud and aerosol problem. At frequencies below about 12 GHz, the surface radiance is proportional to SST and microwaves penetrate clouds with little attenuation, giving a clear view of the sea surface under all weather conditions except rain. Furthermore, at these frequencies, atmospheric aerosols have no effect, making it possible to produce a very reliable SST time series for climate studies. The first satellite microwave radiometers operating at these low frequencies were flown on SeaSat and Nimbus-7, launched in 1978. These early missions demonstrated the

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