POSSIBLE CONTROLS ON THE BULK COMPOSITION AND ORIGIN OF THE EARTH 
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These comments expand and extend ideas in reference (1).

(a) Can radiogenic uranium and thorium supply heat for a core dynamo?

Meteoritic troilite may carry significant U thereby encouraging specula-
tion that U (and Th) rather than K provide radiogenic heating for the Earth's 
core, if it is S-rich.

Using (i) wt. fraction 0.14S, (ii) present heat production 98\mu W/kg for U, 
(iii) mass of outer core 1.85x10^{24}kg, (iv) wt. fraction 0.365 S in troilite, 
the present heat production from meteoritic troilite incorporated into the 
Earth's core would be 7.09x10^{19} W, where y is wt. fraction U in troilite.

Early data on bulk troilite nodules from irons (2,3) indicated signifi-
cant U (Baquedano 6.3ppb; Canyon Diablo 3.5; Gibeon 4.0; Grant 6.5, 24.8; 
Sardis 6.5; Soroti 17; Toluca 10; Toluca-Xiq 2.6) but later data, especially 
fission-track analyses, yielded lower values for separated troilite (ref. 4: 
Augustinovka 0.5-1.0; Cape York; <0.04; Sikhote-Alin 0.1-1.4). Higher values 
were obtained by fission-track analyses for separated graphite (Burgavli, 
10ppb) and screebersite (Bischthube, 1.1; Sikhote-Alin, 6.2). Systematic study 
of the mineralogy and U distribution is needed to evaluate the possible roles 
of contamination, leaching and inter-mineral distribution before the following 
speculation can be evaluated.

Stacey (5) estimated that an adiabatic temperature gradient results in 
transfer of 2.7\times10^{12}W into the lower mantle, and that convection might transfer 
about as much. The 5.4\times10^{12}W would be provided by \sim38ppb U and 130ppb Th in 
the present core and \sim12ppb U and \sim40ppb Th at \sim4.5Gyr (assuming Th/U 3.5, and 
Th follows U). The higher values for meteoritic "troilite" could drive convec-
tion in the early core, but could not drive it now. Other heat sources (e.g.6) 
need consideration.

What fraction of terrestrial Th and U would be needed for the core? The 
Grant value of 25ppb U when applied to the outer core corresponds to 7.7ppb 
for the bulk Earth. For the S1 model (1) with only 14ppb \sim6ppb would go in 
the crust, almost none in the mantle, and the rest in the core. Models with 
higher bulk U, or lower U in the core, would allow extra U in the mantle. 
If U and Th are significant components of the core (or of the mantle, of 
course), He\textsuperscript{4} should be produced, and might be detected after escape to the 
surface. The arguments of Ozima (7) and Fisher (8) with respect to the time 
variation of outgassing of the Earth need extension to cover postulated distri-
butions of K, U and Th between crust, mantle and core. Replacement of U and Th 
in the core by K would result in formation there of \textsuperscript{40}Ar instead of \textsuperscript{4}He. [To 
obtain 5.4\times10^{12}W requires 0.08% K in the present outer core and 0.007% at 
\sim4.5Gyr, which values are controversially high (9). These values amount to 258 
and 22ppm for the bulk Earth, compared to 130ppm in the S1 model (1)].

Existing models for planetary differentiation assume that Th and U are 
partitioned upwards with rising "basaltic" material. Amendment to allow for 
considerable Th and U to partition downwards with sinking troilite would lower 
heat production near the center and increase it near the center. Qualitatively 
it would be easier to differentiate the center of a planet; this is partic-
ularly important for Mars if it has a troilite-rich core.

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POSSIBLE CONTROLS ON THE BULK COMPOSITION

Smith, J. V.

It is necessary to question whether the "troilite" nodules (2, 3, 4) were unleached and free of terrestrial contamination, and whether U is actually in troilite or in adhering minerals such as graphite, silicates and phosphates. To remove many uncertainties, it is important to (a) measure the partition of U and Th among Fe, Ni-rich metal, troilite, silicate and phosphate minerals and both "peridotitic" and "basaltic" magmas, (b) amend heat-radius-time models for planets, and (c) investigate chemical and magnetic consequences for planetary differentiation. Furthermore, if substantial Pb and U are in a S-rich core, it will be necessary to re-evaluate models for differentiation based on Pb-U relationships; e.g. a convecting mantle might strip Pb away from the core and transfer it to the upper mantle and crust.

(b) Oxygen vs. sulfur as the light element in the core.

Ringwood (10) argued against S being the principal light element in the core because it would then be depleted less than Na, K, Mn, Rb, F, Cs, Zn and Cl [14 wt, S in the outer core requires 3-fold greater depletion of K and Rb than S]. Such lower depletion, he stated would require 100-fold depletion of H with respect to S in the solar nebula. This argument is valid only for a one-step condensation and accretion mechanism between the original solar nebula and the final planet. For accretion via planetesimals which undergo chemical differentiation, troilite might sink into a core protected from bombardment, whereas silicate-seeking and other volatile elements would rise to the surface, be bombarded, and swept away as fine debris after disintegrative collisions. There is abundant evidence of differentiated meteorites and asteroids, and oxygen isotope ratios are consistent with formation of Earth and Moon mainly from differentiated types of meteorites.

The eutectic in the Fe-FeS system forms at ~1000°C up to $10^2$ Pa, and it is plausible for troilite-metal bodies to develop and sink in an accreting Earth (Murthy and others). The Ringwood model for the Fe-FeS system should be extended to the Fe-FeO-FeS system, and the argument should be changed to the relative percentages of S and O [and C?] in the core.

(c) Observed surface heat flow vs. models of radiogenic heat production.

The S1 Earth with 130 ppm K, 61 ppb Th and 14 ppb U yields a present heat production of $2.1 \times 10^{13}$ W which is lower than the observed heat flow of $3.1 \pm 0.2 \times 10^{13}$ W calculated from the mean heat flow of $6.15 \pm 0.34 \times 10^{-2}$ W/m$^2$ at the Earth's surface (4) and $4.2 \times 10^{13}$ W calculated from a new estimate of $8.4 \times 10^{-2}$ W/m$^2$ (11). If all heat were instantaneously transported to the surface, and there are no other heat sources, the S1 concentrations must be increased to obtain 50-100% higher heat production. However, before ruling out the S1 estimate, it is desirable to investigate the effects of convection in transporting heat to the surface (including some from the mantle and core?) and other heat sources (heat content of accreting material, perhaps up to solidus temperature; gravitational energy of accretion and core formation). Evidence for incomplete outgassing (e.g., 8, 12) indicates inefficient convection. See abstract by Daly and Richter for a dynamic model.

(d) Origin of the Earth-Moon system.

It may be difficult (1) to retain volatile elements in the Earth if the Moon originates by simple fission (13) or volatilization-precipitation (9). Recent calculations that (a) the giant planets perturbed numerous planetesimals into the inner solar system (14) and (b) that retention of impact debris depends...
POSSIBLE CONTROLS ON THE BULK COMPOSITION

Smith, J. V.

strongly on escape velocity (15), coupled together with (c) the strong possibility that Mars is deficient in volatiles w.r.t. the larger planets Earth and Venus even though further from the sun (16), and (d) presence of many differentiated bodies in the asteroid belt (17), suggests that (i) planetesimals in the inner solar system were highly deficient in volatiles, and (ii) inner planets obtained most of their volatiles from perturbed bodies from the outer solar system. Shoemaker (18) suggested that the early Earth was spunup and fissioned as it grew to about one-half present size thereby providing refractory debris from which the Moon accreted. If the escape velocity of the Moon was too low to allow substantial retention of high-speed bodies perturbed by the outer planets, then chemical differences between the Earth and Moon could be explained by (a) significant accretion of volatiles only by the former body, and (b) retention of Fe-rich metal and sulfide by Earth during fission. Such late accretion must have occurred after establishment of a mantle barrier in order to prevent reaction of late-accreting material with the core. Various combinations of processes invoking fission, disintegrative capture and simultaneous accretion (19) can be envisaged, and chemical constrains on origin of the Earth and Moon become weaker, especially as compositions of planetesimals can be varied in model calculations. Coupled with metal-silicate differentiation necessary for Mercury, and apparent similarity of Venus and Earth, simple composition-distance models for condensation of the solar nebula must be abandoned, and some version of heterogeneous accretion is necessary, at least for the final stage of accretion of terrestrial planets.
