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RADIOACTIVE HEAT SOURCES IN THE LUNAR INTERIOR

James Fred Hays
Department of Geological Sciences
Hoffman Laboratory, Harvard University
Cambridge, Massachusetts 02138

HAYS - Radioactive Heat Sources in the Lunar Interior

CORRECTIONS

Page 3, line 7. Levin and Maeva reference should be 1961, not 1962.

Page 8, lines 7 and 8. "λ's" should be "λ_i's"

Page 14, line 7. Insert after "(KANAMORI *et al*, 1968)" the phrase "and thermal conductivity (MURASE and McBIRNEY, 1970)"

Table 1. Mean radius should be 1738 (KAULA, 1971)
Mean density should be 3.35 g/cm^3 (KAULA, 1971)
References to MacDonald (1959) should be to MacDonald (1959a)

Add the following references:

Levin, B.Yu (1962) in: Z. Kopal and Z.K. Mikhailov, eds., *The Moon* (Academic Press, New York).

Ringwood, A.E. and E. Essene (1970) in: *Proceedings of the Apollo 11 Lunar Science Conference* 1, 769-799, Geochim. Cosmochim. Acta, Supplement *1*.

Sonett, C.P., D.S. Colburn, and K. Schwartz (1968) Nature. *219*, 924-926.

Abstract

Published models for the Moon's thermal history typically imply present day central temperatures far too high to be consistent with the recently proposed lunar temperature profile of Sonett and others, inferred from apparent electrical conductivity of the lunar interior. Furthermore, chemical data on Apollo samples show that the Moon is depleted relative to chondrites in volatile elements, including potassium, and possibly enriched relative to chondrites in refractory elements, including uranium and thorium.

Additional thermal models have therefore been investigated in order to set upper limits on lunar radioactivity consistent with the proposed temperature distribution.

For an initially cold, uniform Moon, devoid of potassium, a maximum uranium content of 23 parts per billion is inferred. This is about twice the chondritic value and an order of magnitude less than the least radioactive lunar rock samples. Accretional heating and more realistic K/U ratios imply still lower uranium contents. Surface concentration of radioactive heat sources is probable only if deep melting has occurred. This, too, implies present day central temperatures greater than 1400°C. Either the Moon has a most unusual geochemistry or the SONETT et al temperature distribution is grossly in error.

1. Introduction

Since the pioneering studies of UREY (1951, 1952, 1955, 1957, 1962) there have been numerous attempts to calculate the thermal history and present day temperature distribution of the Moon (e.g. MACDONALD, 1959a, 1961, 1962, 1963; LEVIN, 1962, 1966; MAEVA, 1965; LEVIN and MAEVA, 1962; FRICKER _et al_, 1967; McCONNELL _et al_, 1967; ANDERSON and PHINNEY, 1967; WOOD, 1971). Most of these workers have based their estimates of lunar radioactive heat sources on the observed compositions of chondritic meteorites. The assumption of chondritic radioactivity distributed more or less uniformly throughout the lunar interior leads immediately to the conclusions that the interior of the Moon has been partially or completely melted and that the present-day internal temperatures lie at or near the solidus curve. A selection of published estimates of present day lunar temperatures is shown in figure 1.

Examination of Apollo lunar samples, however, shows clearly that the Moon does not have chondritic radioactivity. Indications are that potassium is depleted relative to chondrites by an order of magnitude or more, and that uranium and thorium are probably enriched relative to chondrites by a factor of two or more. (e.g. GANAPATHY, et al, 1970; GAST, et al 1970). Furthermore, several lines of evidence, including the triaxial figure of the Moon, the existence of mascons and their persistence for billions of years, the relative paucity of surface features suggesting tectonic activity and internal deformation, and recently, the surprisingly low level of internally generated seismic activity, have led some investigators to conclude that the Moon is a relatively "cold" body with present-day temperatures far below melting throughout the Moon. This conclusion, in turn, requires that the deep interior of the Moon has never melted, since a partially molten interior could not cool appreciably in 4.6×10^9 years even without internal heat generation (UREY, 1962).

At the Apollo 12 Lunar Science conference in January 1971, SONETT et al (unpublished proceedings) presented a new estimate of present day temperatures in the outer 900 kilometers of the Moon, based on a lunar electrical conductivity profile as inferred from analysis of the magnetic field induced in the Moon by the impinging solar wind. This new estimate, shown in figure 1, lies far below all previously published estimates. Similar, though less detailed, estimates have been given by NESS et al (1967) HOLLWEG (1968).

Questions may be raised about various aspects of the SONETT *et al* analysis, particularly the inversion from electrical conductivities to temperatures. Nevertheless, it is the first detailed quantitative estimate of lunar temperatures that appears to be fully consistent with "cold Moon" theories. It seems appropriate therefore to reconsider the question of lunar radioactivity and thermal history to see if models can be constructed that are consistent with the SONETT *et al* temperature distribution.

In fact, if one assumes the temperature distribution to be essentially correct, it proves to be possible to set a rather rigid upper limit on lunar radioactivity. If this upper limit then seems geochemically unreasonable, one is forced to reject the temperature distribution.

2. Method of Approach

The classical equation for the temperature distribution in a spherically symmetric body is:

$$\rho C_p \frac{\partial T}{\partial t}(r,t) = \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 K \frac{\partial T}{\partial r}(r,t) \right) + A(r,t) \qquad (1)$$

(CARSLAW and JAEGER, 1959). If the density, heat capacity and thermal conductivity can be taken as constant, and if the heat source function, A, has a simple form, there are analytical solutions. UREY (1962, and earlier papers) gives solutions for simple boundary conditions that are useful in the lunar problem. In more complex cases, numerical methods must be used. MACDONALD (1959a) outlines a useful technique that has been followed by most subsequent workers. Both Urey's solutions and numerical computations are used in this study, and where direct comparison is possible, give similar results. Density and heat capacity are assumed to be constant and uniform with values indicated in Table 1. Thermal conductivity, K, and heat production, A, are treated in separate sections below. An initial temperature distribution, $T(r,o)$, and a surface temperature, $T(a,t)$, are required to define the problem. Present day mean surface temperature is about -40°C (BALDWIN, 1961). Surface temperature in the past is not well known, but temperatures much lower than at present seem unlikely. Since the intention of this paper is to establish an upper limit to lunar radioactivity consistent with a given temperature distribution, or alternatively to set a lower limit to temperatures consistent with a given level of radioactivity, the initial temperature is taken as uniform at 233°K and the surface temperature is held constant at this value.

Numerical calculations were performed on the IBM 360/65 computer at the Aiken Computation Center, Harvard University. Radial increments of 100 km and time increments of 10^8 years were used for exploratory runs to reduce computation time. The increments were decreased to 20 km and 10^6 years for critical calculations. Time increments were automatically reduced when necessary to meet the stability criterion given by MACDONALD (1959a, eq. 19).

For each model of lunar radioactivity, a temperature profile at $t = 4.6 \times 10^9$ years was computed and compared with the SONETT *et al* distribution.

3. Radioactive Heat Sources

The rate of radioactive heat production per unit mass is given by:

$$A(t) = \sum_{i} A_i a_i x_i \ \exp \left[\lambda_i \ (t_o - t) \right] \qquad (2)$$

where A_i is the present day rate of heat production per unit mass of isotope i, a_i the isotopic abundance ratio, x_i the concentration of the element, and the decay constant. Values for A_i, a_i, and λ are given in table 2; origin of the time coordinate, t_o, is taken as 4.6×10^9 years. The estimation of x_i is the crux of the problem.

In Urey's early papers on the subject (1951, 1955, 1957) he took as his model for the radioactivity of the Moon, the potassium, uranium, and thorium content of chondritic meteorites. He pointed out that an Earth of this composition would be expected to have a surface heat flux approximately equal to the observed terrestrial flux, a fact also noted by BIRCH (1958). Other arguments for chondrites as a model for primitive planetary material are given by MACDONALD (1959b). There is a growing body of evidence, however, that the Earth cannot have a chondritic composition (e.g. GAST, 1960, 1968, 1971; HURLEY, 1968, TAYLOR, 1964). The Earth appears to be systematically depleted relative to chondrites in those elements that are volatile or have compounds volatile at relatively low temperatures. Indeed, chondrites themselves show systematic fractionation of these elements from meteorite to meteorite (LARIMER and ANDERS, 1967, 1970).

WASSERBURG _et al_ (1964) show that despite a variation of 2 orders of magnitude in potassium and uranium absolute abundances, the K/U ratio of terrestrial rocks is remarkably constant at 10,000, and distinctly different from the K/U ratio of chondrites, about 80,000. The terrestrial Th/U ratio, on the other hand, does not appear to differ greatly from the chondritic value of 3.7, though there is considerable scatter. WASSERBURG _et al_ then construct a new model of terrestrial radioactivity based on $K/U = 10^4$ and $Th/U = 3.7$ with uranium content enriched above chondritic values as necessary to reestablish balance between heat production and surface heat flux. They cite additional evidence (HOYLE and FOWLER, 1963) for uranium contents in the range 33 to 52 parts per billion rather than the 10 to 13 ppb of chondrites.

The preferred values for the "Wasserburg" model as well as their estimates of the chondritic values are reproduced in table 3. One or both of these two models have been adopted by most subsequent investigators of lunar thermal history.

With the availability of Apollo lunar samples, it is now worthwhile to reconsider the question of lunar radioactivity.

Analyses of Apollo 11 and 12 lunar rock samples reveal marked depletion relative to chondritic meteorites and relative to terrestrial basalts of a large class of easily volatilized elements including potassium (e.g. GANAPATHY et al, 1970; GAST, et al, 1970; O'KELLEY et al, 1970, 1971; TAYLOR et al 1971).

On the other hand, certain refractory elements including uranium and thorium are strongly enriched in the lunar rocks relative to chondritic meteorites and moderately enriched relative to terrestrial basalts.

A widely but not universally accepted interpretation of these observations requires a high temperature fractionation process either preceeding (LARIMER and ANDERS, 1967, 1970; GAST, 1971) or accompanying (RINGWOOD 1966, 1970; TUREKIAN and CLARK, 1969) planetary accretion. The Earth would then contain relatively more of the volatile-poor, refactory-rich component than the parent bodies of chondritic meteorites, but relatively less than the Moon. Accordingly, we expect the K/U ratio of the Moon to be much less than the terrestrial ratio, and the absolute abundance of uranium and thorium in the Moon to be somewhat larger than in the Earth. The first of these expectations is certainly met, at least in the lunar surface rocks; the second we shall test below.

FANALE and NASH (1971) have investigated potassium-uranium systematics using Preliminary Examination Team data for the Lunar Samples. Figure 2 is from their paper, except that more complete data have been assembled for the lunar rocks. The WASSERBURG _et al_ (1964) relationship: $K/U = 10^4$ is clearly displayed and a similar trend is apparent for the lunar rocks. FANALE and NASH conclude that the overall lunar K/U ratio is almost certainly less than the chondritic value and probably, but not necessarily, less than that of the earth. Data of O'KELLEY _et al_ (1970,1971) yield averages of 2680 and 2066 for Apollo 11 and Apollo 12 crystalline rocks respectively. The corresponding values for Th/U are 3.9 and 3.8. Very similar averages are obtained if data of other investigators are used. Preliminary investigation of Apollo 14 samples (LSPET, 1971) indicates K/U and Th/U values of 1350 and 3.7 respectively.

In this paper, absolute uranium content is chosen as the principal variable. The present day Th/U ratio is taken as 3.8 throughout, and the present day K/U ratio is treated as an adjustable parameter having the following values:

0	(sets upper limit on uranium content)
1350	(average Apollo 14 rock)
2066	(average Apollo 12 crystalline rock)
2680	(average Apollo 11 crystalline rock)
10,000	("terrestrial" value of WASSERBURG *et al*, 1964)
77,000	(chondritic value)

Assuming no loss of heat (roughly true for the Moon's center) the increase in temperature over 4.6×10^9 years associated with one part per billion of uranium (Th/U = 3.8, K/U = 0) is about 40°C. This value is obtained by integrating equation (2) over time and dividing by the heat capacity. The Apollo 12 K/U ratio increases the integrated temperature by 10%, the terrestrial K/U ratio increases it by 43%, and the chondritic ratio by 334% (table 3).

4. Thermal Conductivity

Most previous studies of the Moon's thermal history have followed CLARK (1956) in estimating thermal conductivities by the relationship:

$$K = C + \frac{16n^2 sT^3}{3\varepsilon} \qquad (3)$$

where C is the ordinary phonon conductivity, n a mean index of refraction, s the Stefan-Boltzmann constant, and ε the opacity, or mean extinction coefficient, averaged over all wavelengths and assumed to be relatively insensitive to temperature.

Recent theoretical and experimental studies of the problem by FUKAO _et al_ (1968), PITT and TOZER (1970), ARONSON _et al_ (1970), and SHANKLAND (1970), however, have shown this assumption to be inapplicable to likely planetary materials. Briefly, olivine, pyroxenes, and other iron-containing minerals have an iron absorption peak that broadens at high temperatures, blocking off the transparent window that exists at room temperature. As a result, the opacity increases strongly with increasing temperature and the radiative contribution to thermal conductivity is therefore much less than the T^3 dependence that equation (3) would suggest.

Furthermore the phonon conductivity, itself, is inversely proportional to temperature. The net effect of the decrease in phonon conductivity and the slow increase in photon or radiative conductivity is that the total conductivity remains constant to within fifty percent from room temperature to at least 1100°C (FUKAO, 1969). Direct measurements at high temperature of thermal diffusivity (KANAMORI *et al*, 1968) show these effects clearly. Accordingly, for most of the calculations here, a constant thermal conductivity of .010 cal/cm deg sec was assumed. Values as high as .015 and as low as .005 affect the inferred radioactivities by less than ten per cent. Use of equation (3) with opacities ranging from 3 cm^{-1} to infinity has an equally small effect. The major conclusions of this paper are therefore not affected by the remaining uncertainty about the thermal conductivity.

5. Results and Discussion

The first series of calculations assumes a uniform distribution of uranium and thorium, K/U = zero, and a constant, uniform thermal conductivity of .01 cal/cm sec deg. Comparison with the SONETT *et al* criterion that the temperature must be less than 800°C at a depth of 900 km, yields a maximum uranium content of 23 parts per billion.

Effects of variations in thermal conductivity were then tested. A high uniform conductivity of .015 cal/cm sec deg, as well as use of Equation 3 with an opacity as low as 3 cm^{-1}, allows the uranium content to be as high as 25 parts per billion. Non-zero values for K/U and consideration of higher initial temperatures due to accretional heating or decay of short-lived radioactivities lead to still lower values for the maximum uranium content. For example, a K/U of 2066 (mean of Apollo 12 crystalline rocks), and an initial temperature of 330°K yield a uranium content of 19 parts per billion.

Since the chondritic uranium content of 11 parts per billion would seem to be a lower limit to the possible lunar value, acceptance of the SONETT *et al* temperature distribution, requires the lunar uranium content to lie within the rather narrow limits of 11-25 parts per billion with a probable value of about 19 parts per billion. These values lie substantially below the range of 33 to 52 parts per billion uranium inferred for the Earth by WASSERBURG et al (1964). This conflicts with the argument given above, based on trace element patterns in lunar surface rocks, which predicts a lunar uranium content greater than that of the Earth. A further difficulty lies in the observation that the lowest uranium content so far observed in a lunar crystalline rock is 190 ppb with typical values ranging from 200 to 800 ppb (O'KELLEY et al, 1970,1971). Thus uranium enrichment factors of 10 to 40 would be required during the production of lunar basalts. In fact, the uranium contents of lunar basaltic rocks are similar to those of terrestrial basalts.

Strong upward concentration of heat sources in the Moon would be a possible escape from these difficulties. The most likely mechanism for such upward concentration, however, partial melting throughout the Moon, would require rejection of the SONETT et al temperatures and present difficulties for other "cold Moon" theories (UREY, 1962).

Primary stratification during accretion has been argued for the Earth (TUREKIAN and CLARK,1969; CLARK, TUREKIAN and GROSSMAN, 1971) and such a process applied to the Moon could conceivably produce upward concentration of heat sources. Note, however, that the processes thus far proposed require radically different behavior for uranium and thorium, on the one hand, and for potassium, on the other. If uranium is enriched at the surface, potassium is left inthe interior and vice-versa. Thus, this route of escape appears unpromising.

One is left then with two alternative conclusions:

I. If the SONETT *et al* (1971) temperatures are correct, the lunar uranium content is unexpectedly low: 11-24 x 10^{-9}. Our ideas on the geochemistry of uranium in the terrestrial and lunar interiors must be revised.

II. If the lunar uranium content is greater than 24 x 10^{-9}, *or* if the Moon was ever partially melted at depths exceeding 800 kilometers, then the SONETT *et al* temperature estimate must be decisively rejected.

6. Some Further Speculation About the Moon

At present it is not clear which of these alternatives is correct. In order to explore the range of thermal models that still seem plausible, present day temperature profiles are presented here for three Moon models (figure 3). Models I and II assume an initially cold, uniform Moon, slowly heated up by long-lived internal radioactivity. A surface layer, three hundred kilometers thick, having the thermal conductivity of basalt (.006 cal cm^{-1} deg^{-1} sec^{-1}) is assumed to overlie uniform material with thermal conductivity of .01 cal cm^{-1} deg^{-1} sec^{-1}. Th/U is taken as 3.8, and K/U as 2066.

Model I, with a uranium content of 18 parts per billion yields temperatures closely matching those of SONETT *et al*. Temperatures are, and always have been, far below melting throughout the Moon except for possible near surface transient heating. Such a model is consistent with the lunar shape and mass distribution as well as with the inferred low electrical conductivity. The model fails to explain the high radioactivity and basaltic chemistry of the lunar surface rocks, however, since extensive chemical differentiation and volcanism would not be expected.

Model II has a uranium content of 37 parts per billion, roughly twice that of Model I and near the lower end of the range suggested by WASSERBURG et al (1964) for terrestrial material. Again the lunar interior remains below melting temperatures, but present day temperatures are significantly higher than those indicated by the electrical conductivity data. This model also fails to account for chemical differentiation of the surface rocks.

Thermal profiles similar to that Model II can also be produced by a quite different path. If partial melting has occurred within the Moon, and if potassium, uranium, and thorium were strongly concentrated in the liquid phase and efficiently transported to the surface or near-surface regions, then temperatures within the source-depleted interior remain fixed near the solidus curve. Several such models have been considered by FRICKER et al (1967), McCONNELL et al (1967), and WOOD (1971). These models account for chemical differentiation of the Moon, but, like Model II, they are apparently in conflict with the electrical conductivity data. Furthermore, such wholesale differentiation might by expected to produce a density stratification that would conflict with the moment of inertia. A partially molten interior creates difficulties for the understanding of the Moon's figure (UREY, 1962).

Model III attempts to reconcile the abundant evidence for surface volcanism and chemical differentiation with the evidence for an unmelted deep interior and low present-day temperatures. The Moon is assumed to have an initially cool interior, but an initially hot surface. Such a condition might be produced by rapid accretion (RINGWOOD, 1966; WOOD, 1971) or alternatively by electrical heating induced by an intense early solar wind (SONETT *et al*, 1968).

The initial temperature for Model III (figure 3) was obtained by assuming that the proportion of retained accretional energy increases linearly with radius from zero in the early stages to eighty per cent near the surface, and that this heating is superimposed on a base temperature of 233°K. A very low uranium content of 11 parts per billion is assumed.

In this model the upper 200 kilometers of the Moon is initially partly or wholly molten. Since most of this early surficial heat is readily lost, present day temperatures are within two hundred degrees of those given by Model I. This model is therefore consistent with most of the "cold Moon" evidence, although temperatures 100 to 200 degrees in excess of the SONETT *et al* estimate are required.

The probable importance of accretional heating in the history of the Earth has been emphasized by HANKS and ANDERSON (1969) and by RINGWOOD (1966,1970). Accretional heating of the Moon has been considered by WOOD (1971), Wood's models, however, assume a higher concentration of radioactive elements, and therefore yield present day temperatures that are inconsistent with the inferred electrical conductivity.

7. Speculation About the Earth

If the SONETT _et_ _al_ temperature distribution should be verified by further analysis or by measurement of lunar heat flux (LANGSETH _et_ _al_, 1970), a surprisingly low uranium content for the Moon is unavoidable. Is the WASSERBURG _et_ _al_ (1964) value of 33 ppb for terrestrial uranium content also too high? Reduction of the terrestrial value to 20 ppb yields a terrestrial heat production too low to account for the Earth's surface heat flux. It would then follow that the Earth is now cooling, and that at least a third of the present day terrestrial heat flux is due to additional heat sources such as accretional heating or core formation. A similar conclusion has been reached by HANKS and ANDERSON (1969) on other grounds. Such speculations point up the importance of further measurements relating to lunar internal temperatures.

8. Acknowledgements

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TABLE 1

Parameters used in Thermal Calculations

Mean radius	1735 km	(KAULA, 1969)
Mean density	3.36 g/cm^3	(KAULA, 1969)
Index of refraction	1.7	(MACDONALD, 1959)
Heat capacity	.29 cal/gm deg	(MACDONALD, 1959)
Average thermal conductivity	.01 cal/cm sec deg	(FUKAO, 1969)
Opacity	3, 5, 10, 100, ∞ cm^{-1}	

Table 2

Radioactive Heat Sources
(CLARK, 1966)

Isotope	Heat Production (cal gm^{-1} yr^{-1})	Isotopic Abundance	Decay Constant ($years^{-1}$)
U^{238}	.71	.9928	.154 x 10^{-9}
U^{235}	4.3	.0072	.972 x 10^{-9}
Th^{232}	.20	1.0000	.0499 x 10^{-9}
K^{40}	.21	1.19 x 10^{-4}	.5305 x 10^{-9}

TABLE 3

Chemical Data on Radioactive Elements

	Concentration, ppm					Heat Production, °C (1)
	K	U	Th	K/U	Th/U	
Chondrites (2)	845	.011	.040	77,000	3.7	1875
"Terrestrial avg." (2)	330	.033	.122	10,000	3.7	1859
Lunar Model I	37	.018	.068	2,066	3.8	771
Lunar Model II	76	.037	.141	2,066	3.8	1585
Apollo 11 (3) (10017)	2,430	.83	3.25	2,930	3.9	
Apollo 11 (3) (10003)	480	.26	1.01	1,850	3.9	
Apollo 12 (4) (12052)	540	.27	1.03	2,000	3.8	
Apollo 12 (4) (12013)	21,100	9.8	32.2	2,153	3.3	
Apollo 14 (5) (14310)	4,200	3.2	12.0	1,313	3.8	

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(1) Temperature increase in perfectly insulated material due to internal radioactivity integrated over 4.6 x 10^9 years

(2) WASSERBURG *et al* (1964)

(3) O'KELLEY *et al* (1970)

(4) O'KELLEY *et al* (1971)

(5) R. BRETT, oral presentation at 1971 Annual Meeting, American Geophysical Union

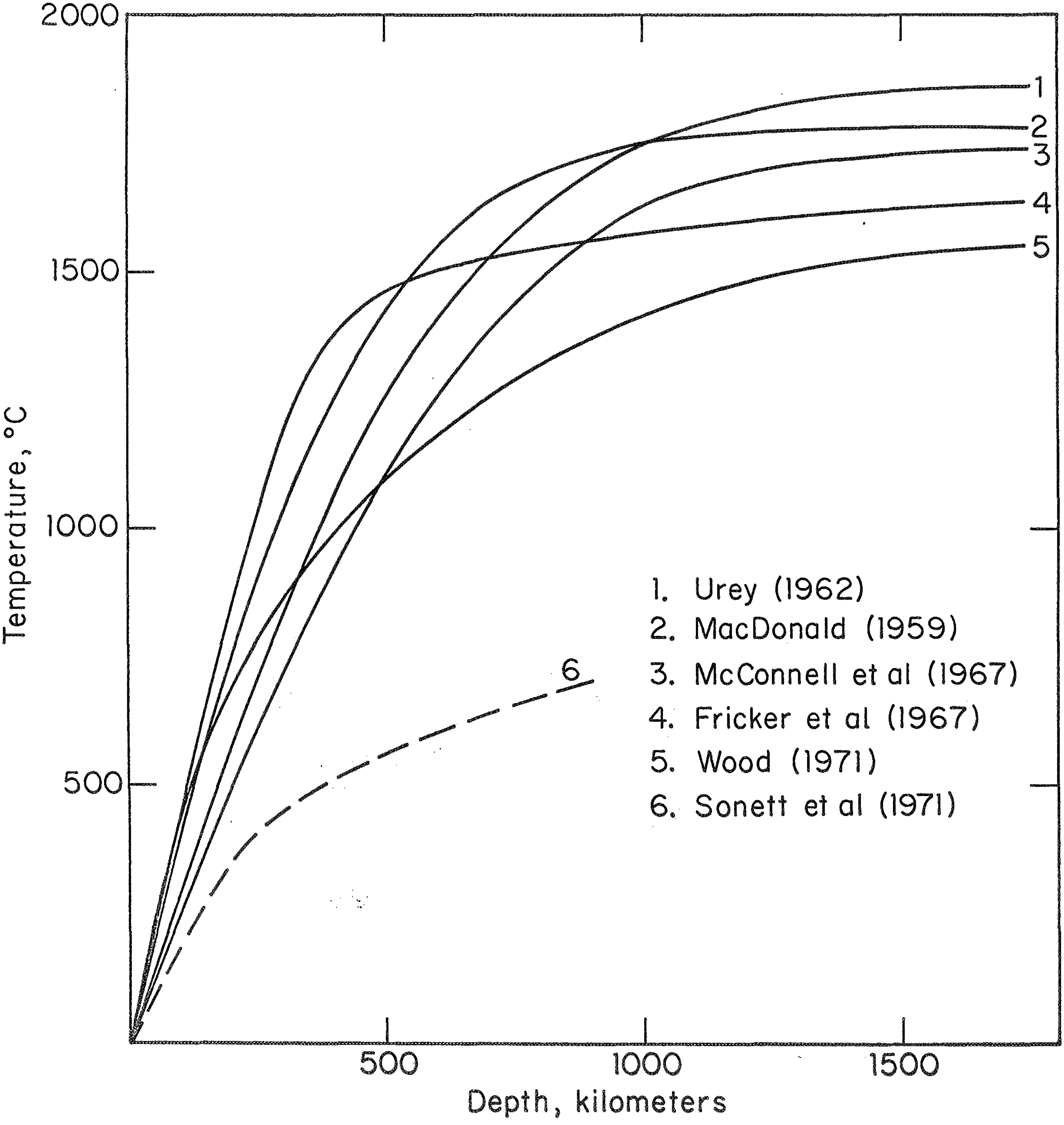
Figure Captions

Figure 1. Selected present day lunar temperature profiles from published literature and comparison with a recent estimate based on inferred lunar electrical conductivity.

Figure 2. Potassium-uranium systematics in terrestrial and lunar material (after Fanale and Nash, 1971). Sources of data are given in Table 3.

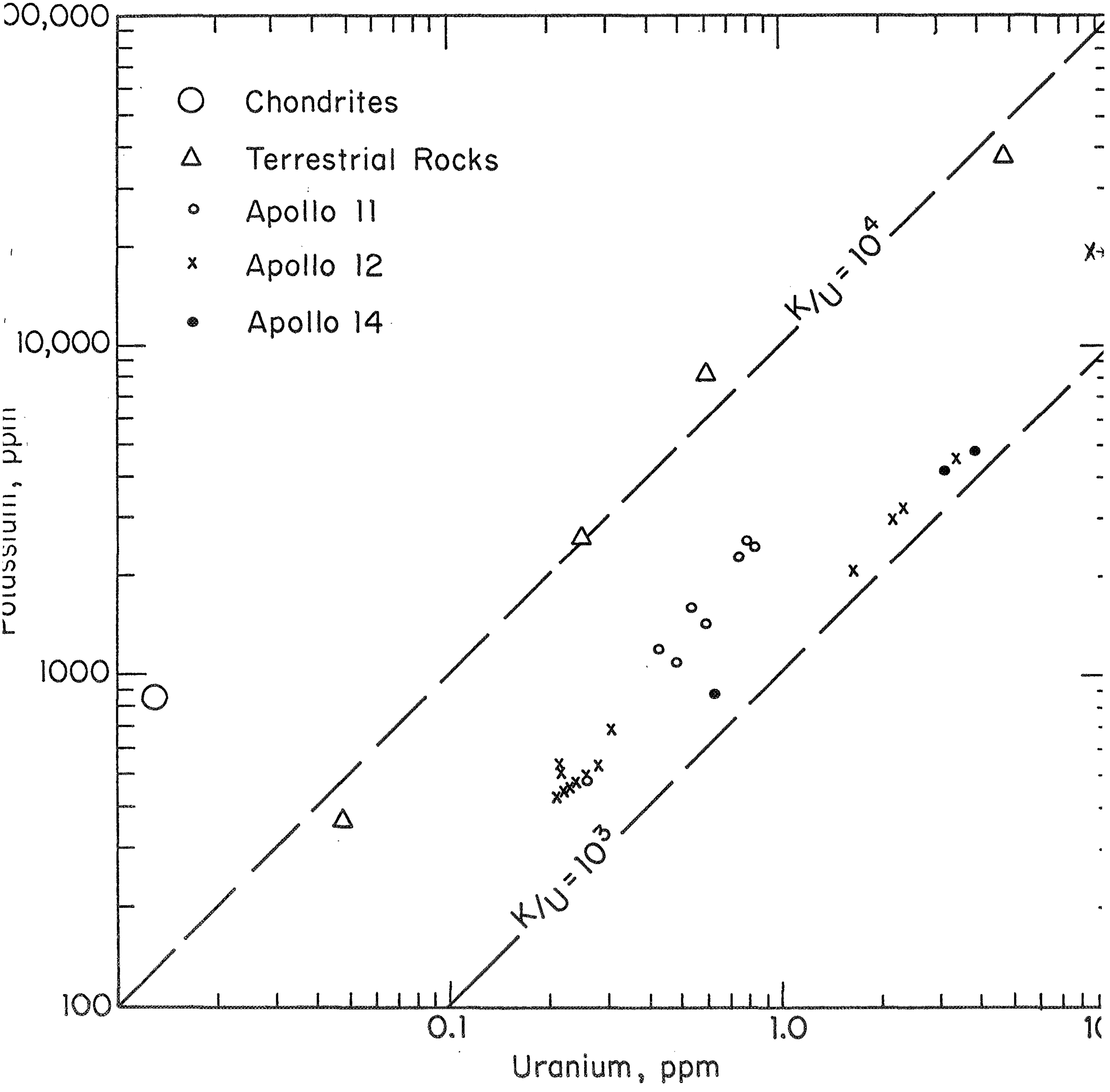
Figure 3. Present day lunar temperature profiles for thermal models I, II, and III.

Figure 1



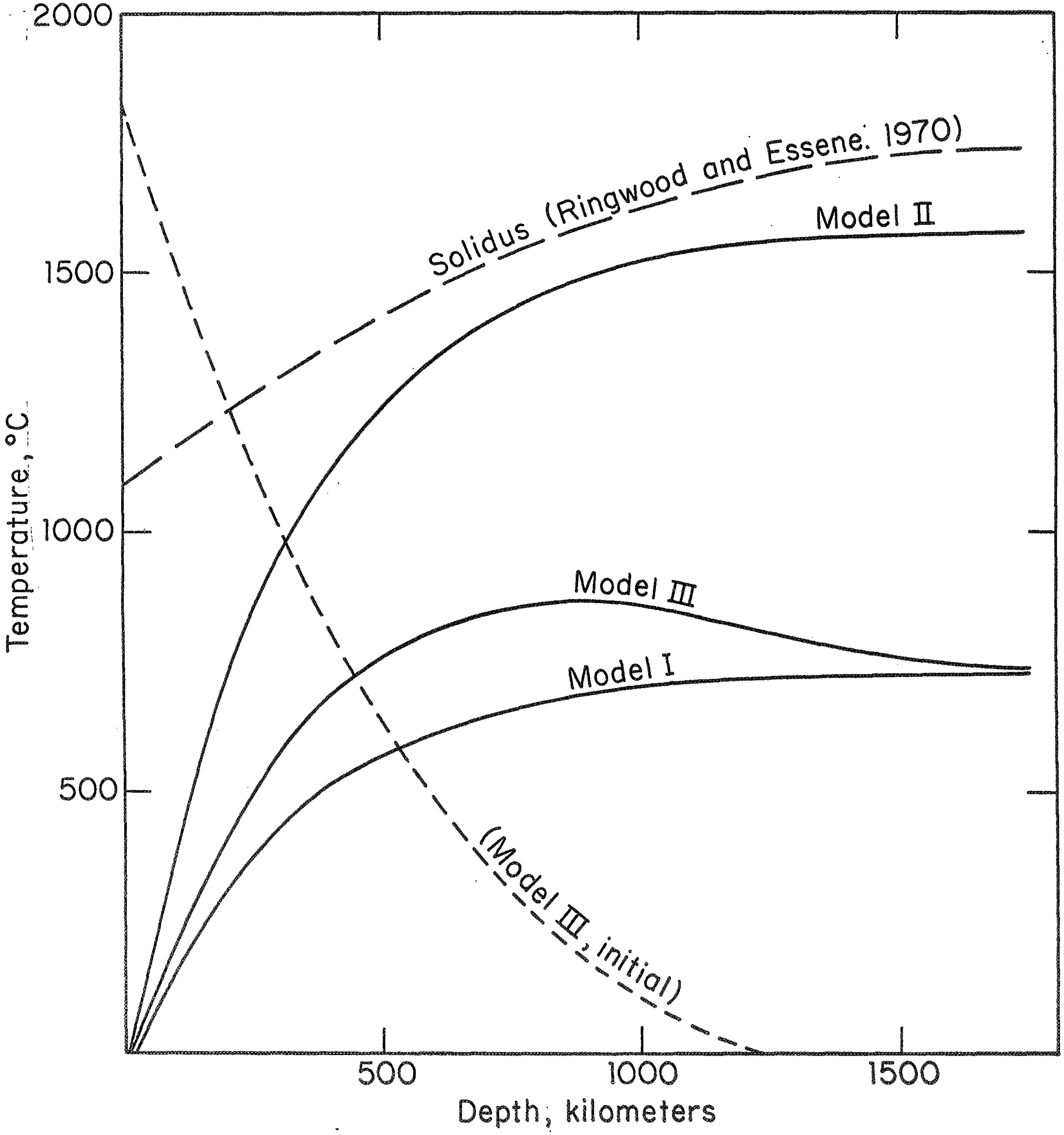
2000
1500
1000
500
Temperature, °C
500
1000
1500
Depth, kilometers
1
2
3
4
5
6
1. Urey (1962)
2. MacDonald (1959)
3. McConnell et al (1967)
4. Fricker et al (1967)
5. Wood (1971)
6. Sonett et al (1971)

Figure 2



○ Chondrites
△ Terrestrial Rocks
∘ Apollo 11
x Apollo 12
● Apollo 14
K/U=10^4
K/U=10^3
00,000
10,000
1000
100
0.1
1.0
1(
Uranium, ppm
otassium, ppm

Figure 3


2000
1500
1000
500
Temperature, °C
500
1000
1500
Depth, kilometers
Solidus (Ringwood and Essene. 1970)
Model II
Model III
Model I
(Model III, initial)