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Kelvin's age of the Earth paradox revisited

Frank D. Stacey

CSIRO Exploration and Mining, Kenmore, Queensland, Australia

Abstract. The age-of-the-Earth paradox that beset geology toward the end of the 19th century has been widely misunderstood. Kelvin showed that if Earth were cooling by thermal diffusion, it would have reached its present state after about 20 Myr, far less time than required by sedimentary geology. The assumptions in this calculation were insecure, and the age estimate would have carried little weight if it had not been comparable to that of the Sun, deduced from its gravitational energy. It was the age limit imposed by the available solar power that inhibited serious rethinking of the terrestrial problem. Contrary to popular supposition, even the discovery of radioactivity did not solve the problem because it contributes negligibly to solar energy. The only possible escape from Kelvin's argument would have been the implausible assumption that the Sun was compositionally heterogeneous, with a strong central concentration of elements such as Si and Fe, in spite of being gaseous and presumably convecting. Since the real Earth age paradox was the inability of available solar power to explain the sedimentary record, it was resolved only by the recognition of thermonuclear fusion in the 1930s. Moreover, although Kelvin's terrestrial heat flux calculation appeared relevant when it indicated an age comparable to that of the Sun, it was not necessary to the paradox and so its invalidation did not remove the paradox.

1. Introduction

After more than a decade of study of Earth's internal heat and implications for its age, *Kelvin* [1863] published a calculation of thermal diffusion from a progressively thickening crust on an initially molten Earth. His conclusion that Earth would have reached its present state after no more than 100 Myr, later reduced to 20 Myr, imposed a strait jacket on studies of the Earth's evolution that cramped geological thinking for the rest of the century [*Burchfield,* 1975]. Known sedimentary layers required hundreds of millions of years to accumulate but were regarded as evidence that was too qualitative to prevail against the physical argument. J. Perry, O. Heaviside, and others pointed out that any mechanism that transferred heat from the deep interior would change Kelvin's conclusion, which was not based on a deficiency in heat sources but on the slowness of thermal diffusion in large bodies. Kelvin's estimated age survived such questioning for a reason that is not always recognized.

Kelvin had also been working on the energy source of the Sun. His original idea was that the luminosity must be powered by the infall of meteorites but evidence of a sufficient concentration of meteorites was not found. *Helmholtz* [1856] had the idea that the energy was more effectively provided by gravitational collapse of the whole Sun, without requiring an infall of fresh material. In a paper preceding his Earth's age calculation, *Kelvin* [1862] adopted the Helmholtz approach, concluding that the Sun could have had power to warm Earth for no more than $\sim$ 20 Myr. Although neither calculation was precise, and both were adjusted at various times, the similarity of the terrestrial and solar age estimates was crucial. They were seen as mutually supporting, but taken independently, it was harder to find a way around the solar calculation.

Kelvin's contemporaries were aware that the forcefulness of his terrestrial argument really derived from the solar calculation. This is clear from an influential article on the age problem, published 3 years before the discovery of radioactivity by *King* [1893, p. 20], who wrote in his conclusion, "...the age assigned to the Sun by Helmholtz and Kelvin (15×10^6 or 20×10^6 years) communicated a shock from which geologists have never recovered." Although King was writing about the age of Earth, it was the calculation on the Sun that really mattered. Hence his final exhortation to his fellow geologists "...the concordance of results between the ages of the sun and earth certainly strengthens the physical case and throws the burden of proof upon those who hold to the vaguely vast age derived from sedimentary geology."

If there had been no solar energy problem, there need have been no age-of-the-Earth paradox. Even without internal heating the present heat flux from Earth, $\dot{Q} =$

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44.2×10^{12} W [*Pollack et al.*, 1993], could be maintained by cooling at an average rate

$$\dot{Q}/\phi = 217 \text{ K per } 10^9 \text{ years} \quad (1)$$

or even less with the heat flux estimate of Kelvin's time, where $\phi = 6.43 \times 10^{27}$ J K^{-1} is the heat capacity. Since internal temperatures of thousands of degrees were contemplated, any mechanism (convection and very high thermal diffusivity were considered) that extracted heat from the deep interior would have allowed a reconciliation of thermal physics and sedimentary geology. However, while the solar energy problem prevailed, such arguments appeared irrelevant. Although the total age of Earth may not have been constrained so securely, sedimentation processes would have occurred only as long as Earth was warmed by the Sun, so it was the duration of the sedimentary record that could not exceed the age of the Sun.

The discovery of radioactivity by H. Becquerel in 1896 was widely believed to have solved the problem, but as Kelvin realized, it did not do so. Rather, the discovery had another negative effect on geological thinking. The need to consider convection disappeared and, in spite of occasional pleas for reconsideration, did not come into general favor for another 60 years. To understand Kelvin's position, especially after the discovery of radioactivity, it is necessary to recognize that the real paradox we are considering arose from the geological evidence for a sedimentary record lasting hundreds of millions of years, while the solar energy on which it depended could have lasted no more than ~ 20 Myr. The terrestrial cooling calculation was an interesting intermediate argument, but it was much weaker than the solar calculation and was not necessary to the paradox. Thus the invalidation of this calculation by the discovery of radioactivity left the paradox intact.

2. Solar Energy Problem

Whereas 19th century physicists allowed the possibility of dramatically extending the age of Earth, as estimated from its loss of heat, they saw no opportunity to do the same for the Sun. With our present understanding of the internal structure of the Sun (mass M, radius R), its gravitational energy is

$$-E_G = kGM^2/R = 6.6 \times 10^{41} \text{J} \quad (2)$$

where $G = 6.6726 \times 10^{-11}$ m^3 kg^{-1} s^{-2} is the gravitational constant; $k = 1.74$ is a numerical coefficient derived from the density profile of the Sun [*Allen,* 1973]. It is larger than the value for a uniform sphere ($k = 3/5$) assumed by Helmholtz, but it only raises the age estimate to an extreme limit of 54 Myr [*Stacey,* 1992, p. 43], still well short of what is needed by sedimentary geology. The more realistic limit is nearer to 30 Myr because a large fraction of the gravitational energy release was retained by the Sun as thermal and compressional energy.

As long as the Sun was believed to be composed largely of hydrogen, and to be compositionally homogeneous, there was no escape from Kelvin's conclusion. Even if one supposed that 50% of the solar mass were of terrestrial composition (mean atomic weight about 26), the balance being atomic hydrogen, a homogeneous mixture would have a mean atomic weight of 52/27, too small to raise the central density sufficiently to give an interesting increase in gravitational energy relative to a solar model with 100% hydrogen. The only possibility of a greatly increased age estimate was to assume that the heavier elements were concentrated in a central core. A (gaseous) core of terrestrial composition and 50% of the solar mass would give sufficient central compression to permit an age of several hundred million years, but the escape of heat by convection makes the persistence of such layering in a gas implausible. It was easier to suppose that sedimentary geology had been misunderstood.

3. Tidal Rigidity and Isostasy

In its original form, Kelvin's calculation envisaged Earth as a molten sphere with a relatively thin solidified crust through which heat was conducted to the surface. He quickly realized that this picture conflicted with the observation of tides. Kelvin himself is credited with the conclusion that the Earth's response to tidal forces indicates rigidity greater than that of steel. The model was therefore modified by supposing that the primitive Earth comprised a solid core surrounded by a molten layer which has now, but only recently (in geological time), also solidified, except in volcanic areas. A detailed rationale for this model was presented by *King* [1893], who appealed to the observation that the melting points of igneous rocks increase with pressure sufficiently rapidly to suggest that Earth would solidify from the inside outward (as we now understand to be the situation in the core). The crust was believed to have solidified from the outside and the molten layer, between the crust and the solid core, would have maintained an adiabatic temperature gradient, less than the melting point gradient and much less than the crustal gradient, convecting as necessary so that the observed heat flux originated from the growing solid core as well as the thickening crust until the two merged.

The supposition [e.g., *Richter,* 1986] that Kelvin's contemporaries were unaware of the possibility of convection within Earth is not strictly correct, although as *King* [1893] saw it, the convection occurred within a fluid layer. Heterogeneity of the crust presented no problem; it was seen as the congealed surface of a convecting layer, not dramatically different from our present view. The demonstration of isostasy, the approximate hydrostatic balance of mountain ranges, by J. H. Pratt and G. B. Airy in the 1850s, one of the triumphs of 19th century geophysics, was also quite consistent with the former presence of a molten layer.

The caution expressed in Kelvin's wording "Age of the Earth as an abode fitted for life" emphasizes the point that Kelvin was dating the time when a complete crust had formed. This did not imply that the Earth had no extended earlier history, from which no geological record survived, but one must presume that with a molten surface it would have cooled very fast and that the vigor of convection would have prevented formation of a permanent crust until the molten layer was reduced to a few tens of kilometers thickness. Such a hypothetical early history makes no appeal to the existence of the Sun, which is required only to explain the subsequent sedimentary record.

4. Rejection of Radioactivity as a Resolution of the Age Paradox

The common supposition is that as soon as radioactivity was discovered, in 1896, the age-of-the-Earth problem disappeared. At least publicly, Kelvin never agreed that this was so and maintained his argument until his death, 11 years later. He has been unjustly maligned for this, as though his reaction was one of pique that his theory was proved wrong. The fact is that Kelvin was right: radioactivity invalidated his terrestrial cooling calculation, but this was a weak argument that was not necessary to the age problem. Heat generation by radioactivity was quickly recognized and completely readjusted the calculation of thermal diffusion from Earth, as considered in section 5, but it had no influence on the solar calculation, and so it did not solve the paradox of the duration of the sedimentary record.

A Sun with the same average composition as Earth would produce about 5×10^{-12} W kg^{-1} of radiogenic heat, that is, a total of 10^{19} W, 40 million times less than the solar output. Even with the completely implausible assumption that the Sun is composed of 100% uranium (with its radioactive daughters), producing 98×10^{-6} W kg^{-1} (without allowing for chain reactions, discovered much later), the total heat would still be only half of the observed solar output, 3.8×10^{26} W. Nothing that was known in Kelvin's lifetime, or for many years afterward, justified the supposition that radioactivity resolved the age problem. However, such was the anxiety in the scientific community to see the paradox resolved that this supposition generally prevailed, essentially by ignoring the solar problem and assuming that to discard the terrestrial cooling calculation is all that was required.

5. Effect of the Discovery of Radioactivity on Geology

The introduction of radiogenic heat to ideas about the thermal history of Earth had a numbing effect. Measurements of the radioactivities of crustal rocks, especially by *Strutt* [1906], fourth Baron Rayleigh, showed that a 10 or 20 km layer of granite could supply the entire terrestrial heat flux without involving the deep Earth at all. The word crust acquired a meaning rather different from Kelvin's idea of a solidified layer on an initially molten Earth. Strutt suggested that radioactivity was confined to such a chemically distinct crust, leaving the bulk of Earth thermally passive. To geologists of a century ago, who had just learned about radioactivity and its strong concentration in the continental crust but knew virtually nothing about the structure of the ocean floor, there was no reason to suppose that any heat flowed from the deep interior. If the deep Earth was passive, then global geology had become a dull subject.

The scene was set for a fixist view of Earth. Radioactivity was identified as the cause of all thermal activity, and this had a shallow distribution. In spite of pleas in the 1920s and 1930s by A. Holmes, V. Meinesz, and R. A. Daly to consider convection and some detailed calculations by *Pekeris* [1935] and *Hales* [1936], thermal models of Earth based entirely on diffusion of heat [e.g., *Lubimova,* 1958; *MacDonald,* 1959] prevailed until the 1960s. By then the paleomagnetic evidence of continental drift had become too strong to ignore, studies of the seafloor had indicated a more mobile Earth than previously recognized, and theories of the origin of the geomagnetic field (section 6) demanded a cooling core which could not be accommodated by diffusion of heat through the mantle.

The final emergence in the 1960s and 1970s of plate tectonics and a thermal history based on convective cooling was a second stage in the abandonment of Kelvin's ideas. The age-of-the-Earth constraint on global geology was believed to have disappeared at the turn of the century, but his view of Earth as a sphere cooling only by thermal diffusion, if at all, survived for another 60 years. If the solar energy problem could have been avoided and the geologically estimated age accepted, then, in the absence of radioactivity, the simple diffusive cooling of Earth would not have explained the heat flux. Geological evidence for an age of at least hundreds of millions of years could have encouraged acceptance of some form of mantle convection by about 1870. Whether the idea would have gained enough strength by 1900 to survive the reintroduction of a diffusive cooling Earth, in response to the discovery of radiogenic heat, can only be conjectured, but a century of global geology could have been very different.

6. Geomagnetic Field

As we now understand, the generation of the main magnetic field of Earth requires a driving mechanism that exhausts heat from the deep interior. If this had been realized in Kelvin's time, it would have provided a basis for questioning his cooling Earth model. What was the evidence available at the time?

As early as 1600 the work of W. Gilbert showed that Earth was a great magnet. His conclusion was confirmed as irrefutable in 1838 by C.F. Gauss [as documented by *Parkinson,* 1983], who used his development of potential theory to show that the field must be of internal origin. By then Gauss would have been aware of the experiments on electromagnetic induction by M. Faraday, first published in 1832 and discussed in detail by *Maxwell* [1954], but he did not make the connection. Neither did anyone else for almost a century.

The concept of deep electric currents appears to have been too difficult, quite apart from the question of how they are caused, and even the matter of ohmic dissipation was not raised. Thus, although clues to the necessity of internal dissipation are obvious in hindsight, they were so far from obvious in Kelvin's time, or for many years afterward, that they had no role in the age-of-the-Earth debate. However, even if they had, would it have made any difference? It would have changed the way in which heat was believed to escape from Earth, but the solar energy problem would not have gone away, so the age problem would have remained.

7. Conclusion: Could the Paradox Have Been Avoided?

Even with our current knowledge of physics and geophysics, but minus all evidence of nuclear processes, would we have been able to advance a convincing argument against Kelvin's age-of-the-Earth estimate? The only possibility appears to be to assume an implausible chemical layering of the Sun.

It really did not matter what one believed about the structure of Earth, the heat sources within it, or how the heat escapes. The age of Earth "as an abode fitted for life" could not exceed the duration of the solar output at a level similar to that at present. To treat Kelvin's terrestrial heat flux calculation as a stand-alone argument is to miss the point. He found a rough coincidence of the ages of Earth and Sun if he assumed that Earth was cooling by diffusion of residual heat. This coincidence justified his assumption. However, the age estimate that mattered was that of the Sun, and this was not upset by rejection of the terrestrial cooling calculation. So Kelvin must be defended for resisting the assertion that radioactivity changed his age estimate. It did not do so because it could not contribute significantly to the energy of the Sun and the solar energy problem was paramount.

Of course, the advent of nuclear dating so reinforced and quantified what *King* [1893, p. 20] referred to as the "vaguely vast age derived from sedimentary geology" that some way out of the solar impasse had to be found in the end. However, did we have to wait for the discovery of thermonuclear fusion reactions? By the time rock ages exceeding 10^9 years had been found, the answer would have been "yes," even with quite improbable chemical layering of the Sun. Gravitational energy sufficient for more than a few times 10^8 years could not have been deduced from any sensible solar model without some fundamentally new physics. However, this new physics appeared only many years after the age paradox was popularly believed to have been resolved by the discovery of radioactivity.

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F. D. Stacey, CSIRO Exploration and Mining,
P.O. Box 883, Kenmore, Queensland 4069, Australia. (f.stacey@cat.csiro.au)

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