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William Thomson – father of thermogeology

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Abstract: William Thomson was among the first scientists to try to understand *thermogeology*: the flow and storage of heat in the Earth. His interest in the field can be regarded as one of the fruits of a life-long love affair with the 'mathematical poem' of Joseph Fourier, which Thomson applied to a wide range of physical problems. For his inaugural lecture at Glasgow University, Thomson somewhat randomly selected terrestrial heat flow as an example to illustrate Fourier's mathematics. Nevertheless, Thomson became 'hooked' on thermogeology: he spent a substantial proportion of his career trying to parameterize his thermogeological conceptual model, one of his goals being to establish the age of the Earth.

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> Are investigations, experimental and mathematical, of underground temperature, not to be regarded as an integral part of geology? … For myself, I am anxious to be regarded by geologists, not as a mere passer-by, but as one constantly interested in their grand subject, and anxious in any way, however slight, to assist them in their search for truth.
>
> (William Thomson, Lord Kelvin, 1869)

Introduction

The ground source heat pump (GSHP) has finally found popularity in the UK as a means of extracting low temperature heat from the Earth and supplying it as space heating to residential and commercial buildings (Banks 2012). A scientific framework of 'thermogeology' has evolved to support those who design and install such GSHP systems. It is intriguing that so many of the crucial innovations in the development of GSHP technology and thermogeology have had a Scottish connection – William Rankine, Horatio Scott Carslaw, Robert Stirling, Dr TGN (Graeme) Haldane, for example.

Shock: Not really a Scot!

In the 1990s, Sanjeev Baskar famously played a character in the show *Goodness Gracious Me*, who insisted that, 'everything comes from India' (Leonardo da Vinci, Jesus, Cliff Richard – all Indian!). I would not wish to fall into the same trap, so let me shockingly reveal to you that our greatest thermogeological hero, William Thomson, Lord Kelvin, was an Irishman, Belfast-born, albeit with good claim to Scottish ancestry (Thomson's paternal ancestors emigrated to Ireland from Scotland during the Ulster Plantation and Claverhouse repressions of the seventeenth century). In 1871 Thomas Henry Huxley declared that William Thomson 'in spite of what I must call the trifling and impertinent accident of birth, is to all intents and purposes a Scotchman' (Thompson 1910).

The Young William Thomson

William Thomson was born in 1824 at 21–25 College Square East, Belfast, adjacent to where his father taught mathematics and engineering at the then newly opened Royal Belfast Academical Institution (RBAI). In 1833, the family moved to Scotland when his father was offered the Professorship of Mathematics at the University of Glasgow. In 1834, aged 10, William was enrolled in the University's classes. Father James was of key importance in his children's education: William's sister Elizabeth recalled some of the key tools that their father used to demonstrate scientific and cultural points (King 1910). Prominent among them are a set of globes and a thermometer in a leather travelling case (Fig. 1).

William and his elder brother, James, graduated together from Glasgow University: passing the BA exams in 1839 and qualifying for their MAs in 1840. William did not, in fact, accept the Glasgow degrees, preferring to wait for Cambridge to gain the more prestigious English qualifications. William moved to St Peter's (Peterhouse) College, Cambridge in 1841, where he excelled and was eventually elected Fellow. He remained in Cambridge until 1845, when he departed to Paris, to work for a short spell with Henri Victor Regnault. His father was ambitious for William to be appointed Professor of Natural Philosophy at the University of Glasgow – and this came to pass on the death of his predecessor in 1846 (Thompson 1910; Lindley 2004).

Kelvin the thermogeologist

William and his brother James had been exposed to geology as teenagers, not least through vacations on the Isle of Arran. However, on a summer visit to Bonn in 1840, they were taken for a three-day geo-excursion in the Rhineland Siebengebirge in the company of Prof. John Pringle Nichol (1804–59) of the University of Glasgow (King 1910; Thompson 1910; Larmor & Thomson 1912). Nichol is credited with introducing William to the mathematical physics approach of Fourier (Gray 1908). Indeed, it was on the same German trip that William immersed himself in

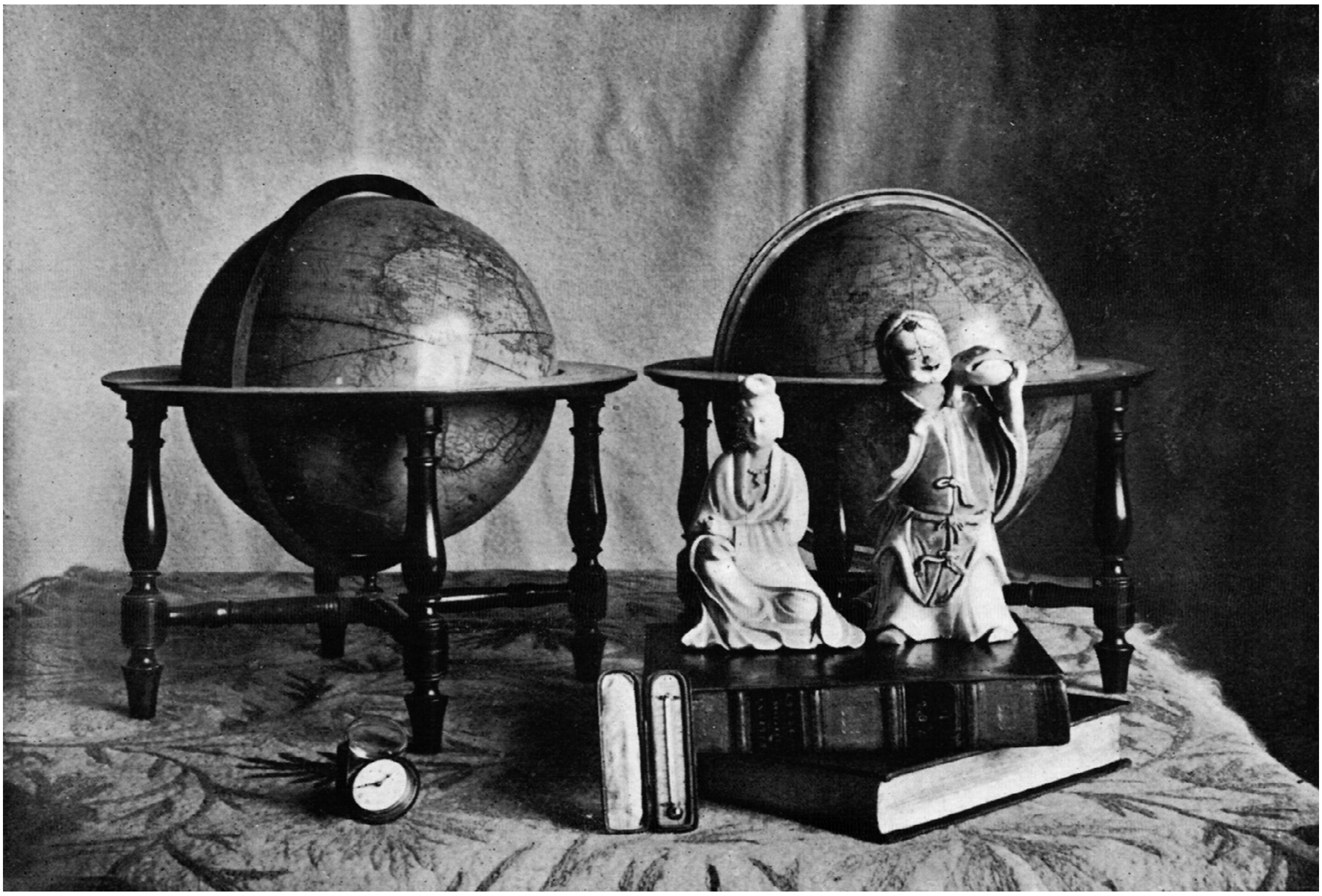

Fig. 1. Relics of William's early education; including those staples of a future thermogeologist, globes of the Earth and a portable thermometer. After King (1910), believed to be out of copyright.

Jean Baptiste Joseph Fourier's '*Théorie Analytique de Chaleur*', which he later described as a 'mathematical poem' (Thomson 1864; a phrase probably originally used by James Clerk Maxwell; Gray 1908). At the age of around 16 (Fig. 2), William dared to submit a paper to the *Cambridge Mathematical Journal*, boldly refuting the ideas of Prof. Phillip Kelland (1808–79) regarding heat theory, in favour of those of Fourier. His second paper continues his defence of Fourier against Kelland, but the topic in this case is the mathematical expression of the motion of heat in a sphere (Thomson 1841; Gray 1908).

Fourier himself had acknowledged a passing interest in thermogeology. As early as the 1820s, he saw that the temperature of the shallow subsurface was governed by its position between two boundary conditions (the atmospheric/solar interface and the geothermal heat flux from the Earth's interior – see also Hopkins 1851). Fourier also knew that daily temperature fluctuations only penetrated a short distance below the surface; seasonal fluctuations somewhat deeper. Most importantly, he realized that the geological cooling of the Earth could be simulated by his (Fourier's) mathematical techniques (Fourier 1820, 1827).

One of William's main tutors at the University of Cambridge was William Hopkins (1793–1866) who, as well as being a mathematical wizard (Thomson and Hopkins are credited with rediscovering the work of George Green), was deeply interested in problems of dynamic geology. Hopkins published on the interior (fluid versus solid) nature of the Earth, the Earth's rotation, mountain-building and the evolution of the Earth's subsurface and surface temperature with time (Hopkins 1851).

Thomson's 1846 inaugural lecture to his Professorship in Glasgow was entitled '*De Motu Caloris per Terrae Corpus*' [On the movement of heat through the body of the Earth], a theme that he was to return to persistently over the next several decades. By all accounts, his 1846 lecture (which he burned after delivery) and his early considerations of the topic argued that, given an initial red-hot or molten global temperature, one could use mathematics to predict the subsequent cooling of the Earth. Moreover, he addressed the feasibility and limitations of inverse modelling, to negative values of time (Thompson 1910), a topic he had already visited in general terms in some of his Cambridge papers (Thomson 1842). The problem of thermogeology was merely one of parameterization. In his '*On Geological Time*' (Thomson 1868) he asks,

> Where must we apply to get evidence? Observation; observation only. We must go and look. We must bore the earth here in the neighbourhood. We must examine underground temperature in other places. We must send out and bore under the African deserts, where water has not reached for hundreds of years. The whole earth must be made subject to a geothermic survey.

William practised what he preached: he continued to tackle the problem of parameterization of his model during much of his subsequent career.

Fig. 2. William Thomson, minus the impressive beard normally associated with him, aged 16, from a pencil drawing by William's sister, Elizabeth, who became an accomplished artist (after King 1910), believed to be out of copyright.

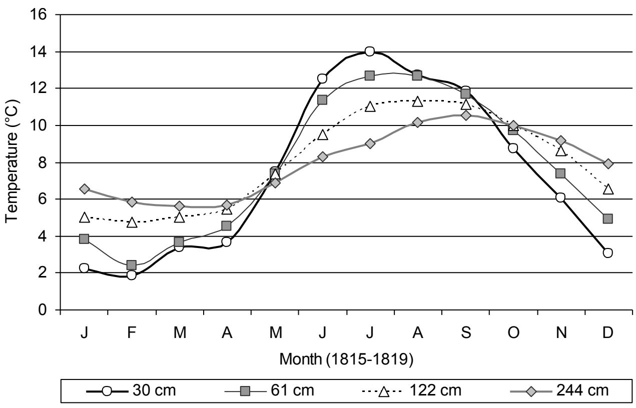

Fig. 3. Temperature data from four thermometers, buried at four different depths, averaged over the years 1815–19, collected from Abbotshall, near Kirkcaldy, Fife, and cited by Forbes (1846).

The quest for thermogeological data

In Scotland, as early as 1815–17, Sir John Leslie, Sir Robert Ferguson and Mr Charles Norbert were collecting temperature data from thermometers buried at various depths in a garden in Abbotshall, near Kirkcaldy, Fife (Forbes 1846, Fig. 3). From 1837 onwards, the Edinburgh-based physicist and glaciologist, James David Forbes (Fig. 4), had also been collecting subsurface temperature data and making what Thomson asserted were the earliest reliable determinations of rock thermal conductivity at the Observatory on Calton Hill, near Craigleith Quarry and at the Experimental Gardens (adjoining the Royal Botanic Garden, Inverleith), in

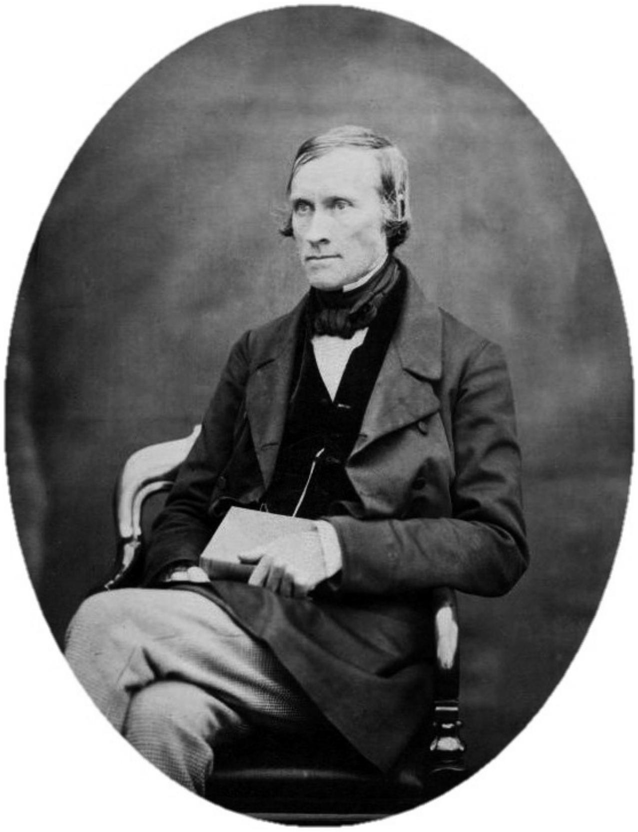

Fig. 4. James David Forbes (1809–68), Edinburgh-based pioneer of thermal conductivity measurement in geological media. Public domain image from Wikimedia Commons.

Edinburgh, by observing the vertical penetration of seasonal temperature signals and applying Fourier's theory (see Table 1 and Thomson 1859, 1861; Anders Jonas Ångström was making similar determinations in Sweden).

Thomson's name appears regularly in annual reports to the British Association for the Advancement of Science (BAAS) of a '*Committee for the Purpose of Investigating the Rate of Increase of Underground Temperature*', founded in 1867: other members included hydrogeologist Joseph Prestwich, geologist and archaeologist William Pengelly, geologists Andrew C. Ramsay and Archibald Geikie (both Scottish), physicists James Clerk Maxwell and Joseph D. Everett. The Committee's annual reports to the BAAS summarized all the latest measurements of thermal conductivity of rocks and of geothermal gradient (Thomson *et al.* 1868, 1871). William Thomson was the first committee member to carry out any thermogeological measurements, in a borehole near Blythswood [central Glasgow], where he observed 'an increase in temperature downwards, but which is not exactly the same in all the strata, the difference no doubt being due to different thermal conductivities ... the average increase is almost exactly 1/50th of a degree Fahrenheit per foot of descent', or 0.036 °C m^{-1} (Thomson *et al.* 1868). The 1871 report notes the very high apparent geothermal gradient at the Slitt Mine near Allenheads, Weardale (a temperature of 18.4°C at 201 m depth, implying a gradient of around 5.4 °C per 100 m), some 130 years before it became the target for geothermal exploration (Manning *et al.* 2007). The Committee also included the duo of mining geologist George A. Lebour and astronomer Alexander Stewart Herschel, who performed

Table 1. *William Thomson's (1859) interpretation of J. D. Forbes' experiments in Edinburgh, based on monitoring annual cyclical underground temperature fluctuations. The exact locations are described on pages 194-195 of Forbes (1846).*

Location	Geology	$\sqrt{\pi/\alpha^*}$	α ($m^2 s^{-1}$)	α ($m^2 s^{-1}$)	Heat capacity (assumed to be cal cm^{-3} °C^{-1})	λ (Btu ft^{-1} °F^{-1} day^{-1})#	λ (W m^{-1} K^{-1})	Heat capacity (MJ m^{-3} K^{-1})
Source		Thomson (1859)	Back-calculated by current author	Thomson (1878)	Forbes (1846), Thomson (1859)	Thomson (1859)	Conversion by current author	Back-calculated by current author
Observatory, Calton Hill	Porphyritic basalt lava	0.11702	7.7×10^{-7}	7.9×10^{-7}	0.5283	23.5	1.69	2.2
Experimental Gardens	'Pure' sand	0.11061	8.6×10^{-7}	8.7×10^{-7}	0.3006	15.0	1.08	1.3
Craigleith Quarry	Carboniferous Craigleith Sandstone	0.06988	2.2×10^{-6}	2.3×10^{-6}	0.4623	53.5	3.86	1.8

#In this column, Thomson has converted to English feet

λ is thermal conductivity; α is thermal diffusivity; α^* is thermal diffusivity in (French feet)^2/year; 1 French foot = 1.06575 English feet. The heat capacity (determined by Henri Victor Regnault) is believed to be volumetric and in calories per cm^3 per °C. The resulting thermal conductivities are remarkably credible. The author's own calculations cast some doubt on Thomson's conversion factors, but differ only moderately

pioneering work in rock thermal conductivity determination from a base at Armstrong College (now the University of Newcastle: Herschel & Lebour 1877; Herschel *et al.* 1879). William Thomson influenced Ayrton & Perry (1878) in suggesting their method for laboratory thermal conductivity determination, while later in his career he also constructed experimental thermal conductivity devices (Thomson & Erskine Murray 1895).

The age of the Earth

William was inordinately irritated by the Uniformitarian philosophy of contemporary geologists, championed by Charles Lyell and encapsulated in James Hutton's assertion that he could 'find no vestige of a beginning – no prospect of an end'. William knew his thermodynamics (he invented the term, after all) and especially the implication of the Second Law that the solar system cannot be in an infinitely stable state: all closed systems suffer entropy increase and eventual heat death. To William it was obvious that geological time had a 'direction': the Earth was cooling down from an original red hot or molten state and was, moreover, slowing in its rotation due to tidal friction (Thomson 1868).

In his most famous paper on the theme (Thomson 1864), William Thomson complained bitterly that, 'essential principles of Thermo-dynamics have been overlooked by … geologists'. In this paper, Thomson considered the possibility that the heat leaking from the Earth (down the observable geothermal gradient) might be derived from internal sources (chemical reaction), external sources (recent passage close to a star) or internal tidal friction, but wields Occam's razor to assume that it is most likely to be derived from simple cooling (loss of sensible heat) of the globe. Thomson then applied Fourier's heat conduction equations to demonstrate that, for a solid, cooling globe, the geothermal gradient (g) at depth z and time t is given by:

$$g = \frac{\Delta T_0}{\sqrt{\pi \alpha t}} e^{-z^2/4\alpha t} \quad (1)$$

He parameterized the model as follows:

- initial temperature of the Earth was $\Delta T_0 = 7000$–10 000 °F (3900–5500 °C) higher than the surroundings (based on a contemporary overestimate of the melting point of rocks);
- rock thermal diffusivity, $\alpha = 400\ ft^2\ a^{-1} = 1.2 \times 10^{-6}\ m^2\ s^{-1}$ (based on Forbes's Edinburgh data and others, Table 1);
- current shallow geothermal gradient $g = 0.02$ °F ft^{-1} = 0.036 °C m^{-1}

and concluded that the Earth would have cooled to its current state in 98–200 million years. Acknowledging our uncertainty about rocks' thermal properties, and how these properties change with increasing temperature, he set a final margin of uncertainty at 20–400 million years.

Thomson's estimates were criticized by geologists and natural scientists, who did not believe that a few hundred million years were adequate to allow the erosion and redeposition of all the observed sedimentary rock sequences. They were led by Thomas Henry Huxley, who politely pointed out that (i) most Uniformitarians were not ignorant of thermodynamics and did not really believe that the Earth was of infinite age, merely that it was extremely old, and (ii) Thomson's model was like a 'mill of exquisite workmanship', but what came out was only as good as the raw materials that went in (an early formulation of the modern computer dictum 'garbage in – garbage out'). Thomson (1869) did not shirk from this criticism and tried hard to quantify his uncertainties, writing, '... in my calculations I have left a wide enough margin to give due weight on Professor Huxley's side to the smallness of our knowledge regarding specific heats, thermal conductivities, and temperatures of fusion'. Ultimately, of course, his model was flawed: it did not allow for internal heat generation by radioactive decay. Henri Becquerel only discovered radioactivity in around 1896.

Kelvin proposes the heat pump

Quite independently from his thermogeological endeavours, William Thomson (1852) was the first person to propose using a 'reversed heat engine' or a heat pump, for extracting low-grade heat from the environment and using it to heat a building. The building in question was Queen's College, Belfast, and it cannot be coincidental that William's brother, James, shortly afterwards took a professorship there and actively worked on space heating and ventilation (indeed, James held an address to the Belfast Literary Society on 14 May 1855 entitled 'On various plans for warming rooms and buildings' – Larmor & Thomson 1912). The Queen's College device was never built, but Thomson's paper describes an 'open-cycle' device using air as the working fluid (Thomas 1948). Although it utilized compression and expansion to change the air's temperature, it differed from a modern heat pump by not employing evaporation and condensation to efficiently absorb and shed heat.

Thomson & Joule (1853) first identified the fact that most compressed gases, when allowed to expand through a valve, throttle or porous plug, undergo a drop in temperature. This Joule–Thomson effect governs the function of the expansion valve at the end of the refrigeration cycle used by most modern refrigerators and ground source heat pumps.

The idea of using heat pumps to extract heat from the ground was subsequently patented in 1912 by the Swiss Heinrich Zoelly and they began to be used for this purpose in the 1930s and 1940s. Dr TGN 'Graeme' Haldane constructed a prototype to extract heat from spring water to heat his home at Foswell, Perthshire in 1927–8 (Banks in press). Ground source heat pumps are commonplace today.

Kelvin's etymological legacy

William Thomson was not afraid to introduce new words and terms to the English language. It is believed that he was the first person (Thomson 1849) to use the term 'Thermodynamic'. The word was adopted and popularized by others, especially Thomson's close friend, James Prescott Joule.

Thomson (1878) more consciously invented the term 'thermal diffusivity' to describe the ratio of thermal conductivity to volumetric heat capacity in rocks.

His most enduring legacy is, of course, derived from his choice of title on being granted his peerage in 1892: Baron Kelvin of Largs. The title is taken from the name of the narrow river (*Caol Abhainn* in Gaelic) Kelvin, running through the grounds of his beloved University of Glasgow. Thus, this modest Glaswegian river went on to give its name to the absolute temperature scale, first proposed by Thomson in 1848.

Lord Kelvin passed away in December 1907 at his home at Netherhall, Largs, following a chill. He left an astonishing legacy of scientific and engineering work, but no children. His former students carried his legacy onward, however: notably, Horatio Scott Carslaw (Banks 2014), whose work inspired the Theis well function, and the analytical descriptions of many subsurface heat exchanger geometries.

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