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Perspective

Paul Younger — a pioneer in UK geothermal energy

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Abstract

Paul Younger was an outstanding geologist born and bred in the northeast of England and although he spent time away, his geological umbilical firmly fixed him in the region encompassing the counties of Northumberland and Durham their cities, towns and pit villages; an area for which the geology underpinned the industrial and social development. The linkage between geology and industry is commonly reflected in the groundwater of area and it was this that first stimulated Paul into research. He became a hydrogeologist. But Paul recognised that there is more to adit water outflow than solutes. The water told another story, one of heat below the surface, copious amounts of it. The warm and tepid waters encountered by Paul in the region set him thinking about geothermal energy. In 2004 he became the first person in 20 years to drill a dedicated geothermal appraisal well in the UK at Eastgate in Weardale. He followed up with a second well in Eastgate in 2010 and a third in central Newcastle in 2011. Paul was passionate about the energy transition and saw geothermal energy as a vast resource, easily won and one which could affect a fundamental change in the way we heat our homes and places of work. Sadly, Paul did not live to see the UK National Geothermal Centre formed in 2024. It is nonetheless a product of his vision.

Keywords: Paul Younger; geothermal energy; Weardale; hydrogeology

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1. Introduction — Paul's journey and epiphany

The aim of this paper is to describe the geothermal research and outputs from Paul Younger (1962–2018). Both of the authors worked closely with Paul. Charlotte Adams (CAA) undertook her PhD under the supervision of Paul at Newcastle University 1996–1999 and subsequently worked as Paul's Research Associate. Jon Gluyas (JGG) met Paul shortly after joining Durham University from industry late in 2009. By the time CAA met Paul he was already an established hydrogeologist with experience in his local area of NE England (leading work on mine water management and treatment), the Thames Valley, Bolivia and Oklahoma, USA. It was through work with CAA on treating discharges from abandoned mines that awakened Paul to a new area of research in geothermal energy which he pioneered in the UK from the beginning of the new millennium up until his untimely death in 2018. CAA was researching mine water remediation in the Northern Pennines. Paul was always eager to support his students field work, the North Pennines in the depths of winter occasionally being less cold than expected! This was due to warm connate water issuing from old mine adits. A search of mining data by CAA and Paul revealed that miners had in the past remarked on how warm the water was that flooded into the mines. Recognition of the geothermal and hydrogeochemical characteristics of the connate water proved the stimulus for Paul's work to come on geothermal energy.

In some respects, Paul picked up on the great work of Tony Batchelor, Pete Ledingham and others who worked on the Cornish hot-dry-rock geothermal exploration wells of the 1980s [1] and between 2004 and 2011 drilled three deep geothermal boreholes in NE England, the first such wells drilled specifically for geothermal energy outside of Cornwall and Southampton [2] for several decades.

2. Eastgate — 2004

The Weardale Granite (Figure 1) was discovered in 1961. A well at Rookhope (Figure 2) was drilled following the work of Bott and Masson-Smith [3] who measured gravity and magnetic anomalies in the Northern Pennines and postulated the presence of an unexposed granite. The granite encountered in the Rookhope borehole and later named the Weardale Granite (Figure 3), proved the Bott and Masson-Smith hypothesis. It also delivered two surprises. The top of the granite was eroded, indicative that after emplacement it had been exposed at the Earth's surface, and the temperature recorded at 808 m drilled depth was 40 °C [4], significantly warmer than expected. The high heat flow encountered in Rookhope was confirmed by the Woodland Borehole drilled in 1962 immediately south of the granite (Figure 4). It reached 499 m where a temperature of 29.3 °C was measured. That the heat from the granite could be utilised seems not to have elicited much interest until Paul began to think of the possibilities for geothermal heat utilisation for the planned eco-village to be sited at the closed LaFarge Blue Circle cement works at Eastgate.

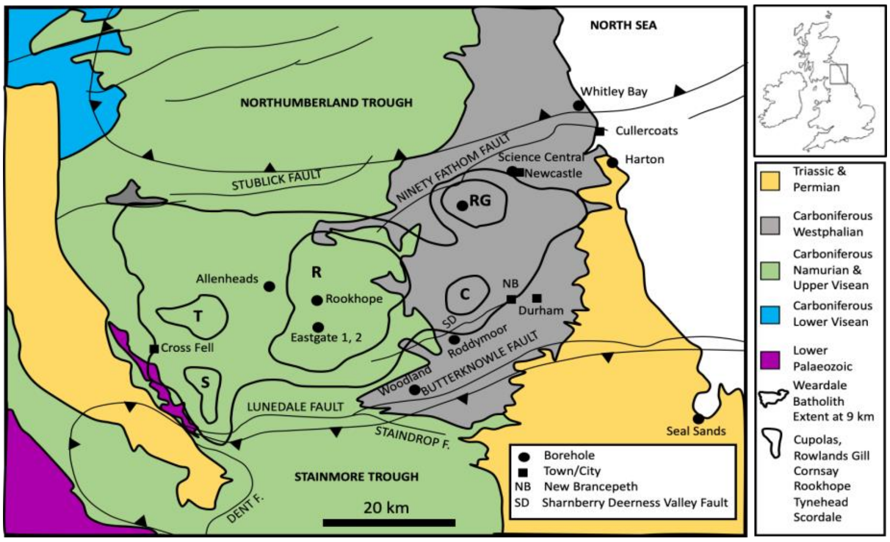

Figure 1 Key geological features of Weardale and adjacent areas (from Gluyas *et al* 2021 [5]).

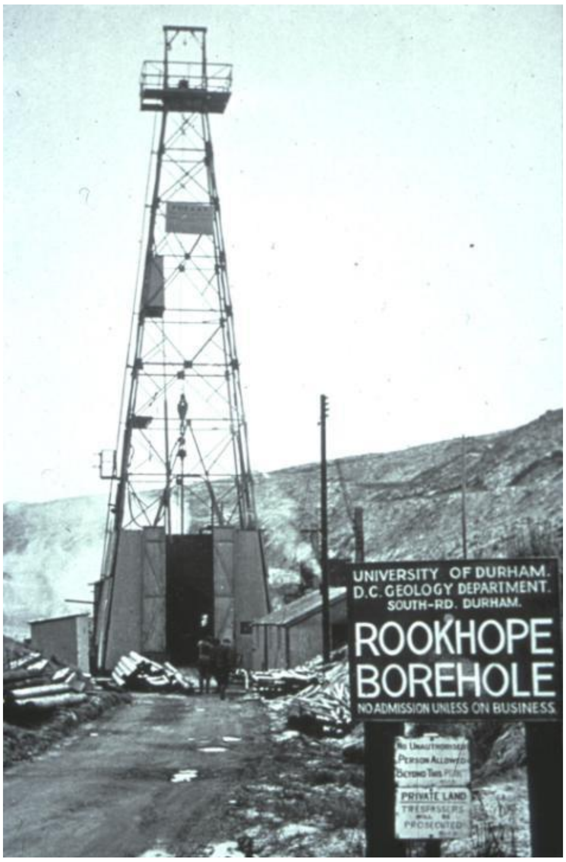

Figure 2 The Weardale Granite was discovered with a borehole drilled at Rookhope in County Durham (photograph found on a windowsill within the Department of Earth Sciences, Durham University by Jon Gluyas).

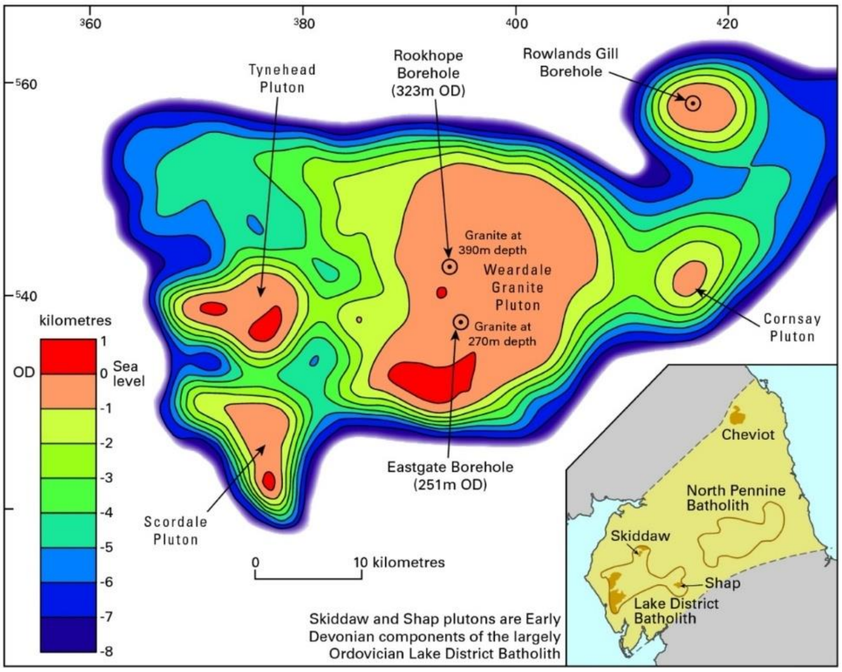

Figure 3 Location of the Weardale Granite pluton (Figure 36 from Stone *et al.* [6]).

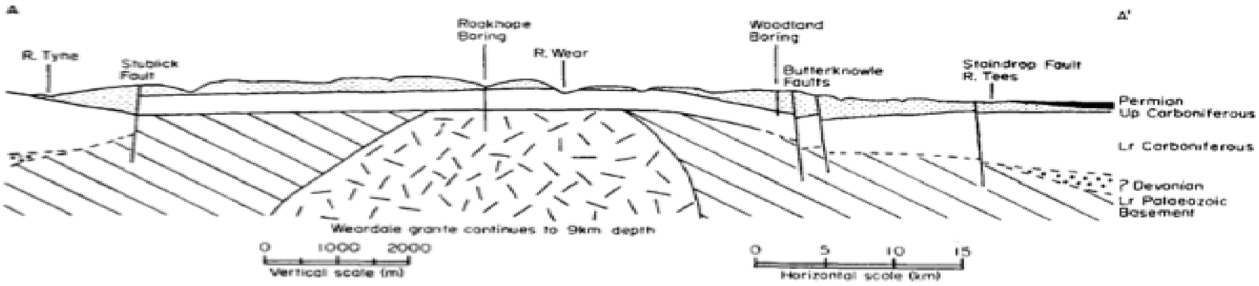

FIG. 2. Deep geological structure along line A–A' (Fig. 1) passing through the positions of the Rookhope and Woodland boreholes. The subsurface shape of the Weardale granite and of the Carboniferous basins has been inferred from gravity anomalies (Bott 1967).

Figure 4 North-south cross section of the Weardale Granite and its overburden (from Bott *et al.* 1972 [7]).

The story of that reawakening is best told by Paul himself and the following section is from an article originally by Paul and published in Geoscientist Magazine, November 2005 and then reproduced in Geodrilling International in early 2006 [8]. We have added the photographs in this section, all of which were taken by Paul.

"The closure in 2002 of the LaFarge Blue Circle cement works in Weardale, meant the loss of 147 jobs and around £7 million (US$12.4 million) from a local economy still reeling from fluorspar mine closures and the foot-and-mouth crisis.

The Wear Valley Task Force – a consortium involving Wear Valley District Council and One North East (ONE) [a Regional Development Agency] – engaged consultancy firm PB Power to model redevelopment plans for the site, to create a renewable-energy village and activities centre, harnessing wind, hydro, solar and biomass energy. A chance conversation between a PB director and ourselves added a further dimension to this vision. In the late 1980s, when Cambokeels Fluorspar Mine was in production, a persistent saline water feeder was encountered in the eastern forehead of the mine coming from unworked portions of the Slitt Vein, which lie beneath the cement-works property. Geothermometric calculations that were made suggested the saline water might have equilibrated at a temperature as high as 160 °C.

More recently, repeated mine water analyses (which we had made during the last years of mining at nearby Frazer's Grove Fluorspar Mine and which lies on a very similar vein a few kilometres north of Eastgate) had revealed that structures of the same type as the Slitt Vein are associated with very high geothermal gradients.

On this basis, we were confident that a serious geothermal prospect, enough for 'direct heat use' applications, could be found beneath the old site of the cement works. This possibility so appealed to the Task Force that it obtained £500,000 from ONE to investigate the possibility. We estimated we could drill an exploration borehole to around 1,000 m for that money – certainly deep enough to prove whether or not our theory was true.

First, we used five inclined 50 m boreholes to locate the Slitt Vein on LaFarge land, beneath a thick till mantle (Figure 5). On August 26, 2004, French drilling company Foraco began the deep borehole (Figure 6), under the watchful eye of Dr. Sorcha Diskin and Dr. Rick Smith. The initial 273.5 m of the borehole traversed thoroughly-veined, heavily-water-bearing sedimentary rocks and Whin Sill dolerite. It was only after drilling 133 m into the Weardale granite (only the second borehole ever to do so) that we were able to case-out all overlying aquifers and continue drilling in a dry hole. We were a bit nervous that we might have overdone it, and we would never see our beloved saline water again.

Suddenly, at 411 m depth, the entire drill string dropped by 0.5 m. We had apparently hit a 0.5 m-wide open void in supposedly solid granite. The air column in the borehole was pushed out ahead of a rapidly rising water surface, which thankfully settled 11 m below ground (Figure 7). Pump as we might (>60 m^3/h) we could make no impression on it. Granites are not supposed to do this. It had to be open fractures associated with the Slitt Vein (Figure 8). So we drilled on, with a great attrition rate for drill bits in the hard *granite and hypersaline water (a Ca-Na-Cl brine, about 50% saltier than the sea). On December 4, 2004, at 995 m we called it a day. A few days later came the most nerve-racking section of the job: watching the borehole being logged for temperature. It proved worth the wait: a bottom hole temperature in excess of 46 °C (more than 11 °C greater than you would expect were the geothermal gradient on the UK average).*

It has been known that the Weardale granite is a high heat producer, since the drilling of the 808 m Rookhope borehole by Sir Kingsley Dunham's team in 1960–61. What is news is the presence of high fracture permeabilities at depth, no doubt associated with the Slitt Vein. In practical terms, we have already proven a geothermal resource as promising as any previously identified in the UK. Further borehole test work, to quantify heat and flow parameters, is planned.

Meanwhile, we are already sure that even this exploration borehole could supply enough warm water to support a thermal spa attraction in the chilly North Pennines. With further drilling, much greater thermal resources might be tapped."

A second borehole was drilled – Eastgate 2 but it was only executed 6 years later in 2010 by which time plans for the eco-village, which had come so close to fruition were put on hold due to the global financial crisis of 2008 [9].

Figure 5 Five inclined boreholes to 50 m were drilled before spudding Eastgate with the aim of locating the Slitt Vein in the subsurface (photo by Paul Younger).

Figure 6 Eastgate drill rig (photo by Paul Younger).

Figure 7 Eastgate produced hot saline water on test pumping in February 2005 (photo by Paul Younger).

Figure 8 Still from borehole televiewer video. The blurred white spots are material flowing past the camera at 411 m where a major open fracture system was encountered (photo by Paul Younger).

3. Eastgate 2 — 2010

A plan to drill Eastgate 2 was conceived shortly before JGG first met Paul in November of 2009. JGG arrived from industry to academia in October 2009 and joined Durham University Earth Sciences department. As part of the familiarisation process, he was made aware of the failed bid that Newcastle, Durham, and other universities had made to host what would become the Energy Technology Institute (ETI). That bid was led by Paul Younger, and we understand it to have been a near miss to land ETI, won narrowly by Loughborough University. It was no surprise to JGG that when invited to a week-long workshop hosted by BP to investigate the potential for geothermal energy development as part of oil and gas field operations, Paul would be invited too. Held in West London, the workshop was an intense four and a half days' worth of familiarisation, data analysis, interpretation, Imagineering and more. There was however a midweek, Wednesday afternoon, relaxation and recuperation trip by coach to central London to see the Moctezuma exhibition British Museum. Paul and Jon (JGG) sat together on the coach and a plan hatched.

The UK government had, just a matter of weeks, earlier in 2009 announced that the Department of Energy and Climate Change would award up to £4 million for their deep geothermal energy challenge fund for projects to be executed 2009–2010 [10]. PY told of his plan to drill a second well at Eastgate. Planning permission had already been granted but 'we would still need to move fast' if we were to bid for funding, win, appoint contractors, drill, and complete the well in the short timeframe dictated by government.

Figure 9 Eastgate 2 drilling operations, 1st March 2010 (photo by Jon Gluyas).

Figure 10 Location of Eastgate 1 and Eastgate 2 in Weardale County Durham. Location NY 94526 38126, datum level 253.27 m above OD (from Paul Younger, 2010 [11]).

Funds of £461,000 were awarded from the Department of Energy and Climate Change on the 18th January 2010 and drilling of Eastgate 2, located about 700 m from the first well drilled at Eastgate, began shortly thereafter [11,12] (Figure 9). The well was planned to drill to 420 m below ground level to form a doublet with the original well [10]. Unlike the original well at Eastgate, Eastgate 2 was not drilled to intercept the Slitt Vein, but deliberately located some distance away (Figure 10) such that results from it would enable differentiation between two hypotheses as to why the original well had flowed water so easily. The most likely explanation for the high-rate flow in the original well was that it intercepted a naturally open Slitt Vein. The less likely hypothesis was that the whole of the upper surface of the granite was weathered and hence permeable. Knowing which of these two models was correct was of importance to development of the geothermal resource for it would dictate the locations of any future wells.

Significant problems were encountered in the interval from 52 m to 257.5 m below surface. Fractured and karstified limestones allowed formation water ingress as well as loss of drilling fluids and grout. An intermediate casing run also failed with casing collapse below 137 m. A CCTV inspection revealed that there was no grout behind the casing and it seemed likely that the grout had instead penetrated into the Melmerby Scar Limestone beds at 239 m and 257.5 m. The well was securely capped, and a new bore began. For the redrill, very thick-walled casing was used to mitigate the risk of any collapse due to loss of grout into the formations. It was successfully drilled through the Carboniferous limestones and associated sandstones and shales. The Weardale Granite was encountered at 288.5 m as prognosed and the well terminated slightly shallower than planned at 420.43 m (Table 1). The granite section is unlined and stable in the hard granite.

Table 1 Main geological horizons penetrated.

Unit	Thickness (m)	Drilled depth to base (m)
Unconsolidated deposits (Quaternary till)	10.5	10.5
Tynebottom Limestone	11.0	63.0
Sandstone (fine-grained)	23.0	93.0
Jew Limestone	4.0	102.0
Great Whin Sill (dolerite intrusion)	58.5	167.5
Lower Little Limestone (Upper Leaf)	4.0	176.0
Lower Little Limestone (Lower Leaf)	2.5	184.0
Upper Smiddy Limestone	9.2	209.2
Melmerby Scar Limestone (Upper Leaf)	10.0	239.0
Melmerby Scar Limestone (Middle Leaf)	13.0	257.5
Melmerby Scar Limestone (Lower Leaf)	3.0	265.0
Conglomerate with granite clasts	1.0	284.0
Top Weardale Granite	-	286.3
Terminal depth (167.4 m below OD)	-	420.4

The top 3 m of the granite is pale greenish and weathered. Below this weathered zone, the granite is predominantly grey, uniform, relatively fresh aphyric, with quartz, white potassium feldspar (often altered to pale greenish yellow), muscovite and biotite. There are occasional bands of biotite-rich granite. The short run of core (Figure 11) reveals some tight, shallow-dipping and sub-horizontal fractures.

The Weardale Granite intercepted by the Eastgate 2 Borehole has very low permeability. A brief rising head test was conducted after completion of the borehole from which an average permeability was calculated. It being less than 0.01 darcies for the 131.5 m interval of granite penetrated by the borehole and much less than in the original Eastgate borehole. This was taken to indicate that the high permeability at 411 m in Eastgate 1 is tectonic in origin, due to fractures associated with the Slitt Vein.

Figure 11 Weardale Granite core cut in Eastgate 2 (photo by Paul Younger).

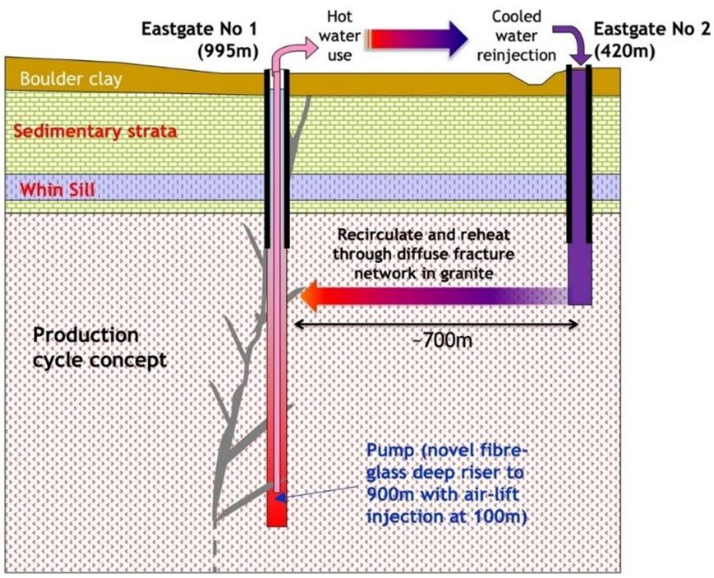

Figure 12 Development concept for the Eastgate well doublet (drawn by Paul Younger).

Paul began to formulate a development concept for the well pair, in which the deep Eastgate 1 well was used for production and the shallower Eastgate 2 well for re-injection of spent water from which the heat had been removed. Transmission within the rock would have occurred via natural fractures likely enhanced by injection of the cooled water through thermally induced shrinkage of the rock mass (Figure 12).

However, the plan for an eco-village was abandoned with the change in UK government in May 2010 and the Regional Development Agency, which had backed the proposal, dissolved.

4. Newcastle Science Central (Helix) Deep Geothermal Borehole — 2011

In 2005, Newcastle became a Science City, a scheme developed by the then UK Chancellor of the Exchequer, Gordon Brown. This government scheme was aimed at making science, technology and innovation the driver for economic growth. To meet this aim, Newcastle Science City partnership consisting of Newcastle University, Newcastle City Council and One NorthEast was formed and it purchased the site in central Newcastle that had been the Scottish and Newcastle Brewery. The land to be redeveloped was called Science Central (it was rebranded as Newcastle Helix in 2016) and as part of that development Paul was able to persuade the partnership to drill a geothermal test bore to 1.8 km in the midst of the site (Figure 13) and about 3 km south east of the Ninety Fathom Fault, the major bounding fault on the southern edge of the Northumberland Trough (basin). The plan for the well was to drill to the Lower Carboniferous Fell Sandstone formation, a known and prolific potable aquifer in Northumberland [13]. The drilling and testing of Science Central are reported in Younger *et al* (2016) [14]. The well was eventually drilled to 1.8 km following substantial drilling difficulties. The Fell Sandstone was penetrated but was finer than had been seen elsewhere and on test the well failed to flow at a significant rate. It was not clear why the well did not flow. It had been drilled with minimal budget and both the logging run and well test were conducted as cheaply as possible. There seemed to be three possibilities; the sandstones were thoroughly cemented (mineralised) close to the Ninety Fathom Fault, the Fell Sandstone encountered in the well was different from that seen further north in Northumberland or possibly the well was damaged by the drilling process. The question remained unanswered until 2022 when completion of research master’s degree by Rory Sutton [15] determined that the most likely cause of failure was a combination of finer grained cemented sandstone at the Science Central location and an absence of natural open fractures.

Figure 13 Science Central drilling rig July 2011 (photo by Jon Gluyas).

5. BritGeothermal — 2012

Co-operation between Newcastle University and Durham University had delivered funding for Eastgate 2 in 2010 and the following year the same academic partnership with support from Newcastle City Council began to drill the Science Central well. The forced changes to the drilling specification and problems encountered in the shallow section meant there was a £150k shortfall in money to drill the well to the pre-spud plan of 1.8 km. The funds were sourced from the BGS who at the time had JGG as Chair of the BGS Board. The 3-way partnership secured the relationship between Newcastle, Durham and the BGS that had been started in March 2010 during the drilling of Eastgate 2. This partnership recognised that together it had done something special to further the case for geothermal energy in the UK. Not only had it delivered yet another research borehole, but its members had brought the opportunities to use geothermal energy in the UK to the notice of the governments pre 2010 and post 2010 and senior civil servants and leading to the SKM report [16] and Atkins report [17] on the UK's geothermal potential.

Sometime during early 2012 the group comprising Paul Younger and co-researcher Rob Westaway (Newcastle), Jon Gluyas and Charlotte Adams

(Durham) and Jon Busby discussed formalising the relationship and set about founding the BritGeothermal research joint venture with its distinctive logo (Figure 14). During the foundation process Paul moved to Glasgow University from Newcastle University and took up the prestigious Rankine Chair of Engineering. Where once there were 3 partners, now there were 4. In December 2012 the research partnership was announced, and a website hosted by BGS was launched with the four partners sharing costs equally and CAA installed as partnership manager working out of Durham University's Energy Institute (DEI). There were some immediate successes. The research partners, led by CAA meet with Lord Jenkin in Westminster and managed to decouple geothermal energy exploitation and shale gas fracking in what was then the UK Infrastructure Bill and became an act in 2015 [18]. This was particularly important because subsequently shale gas exploration and associated fracking technology became very controversial and let to a moratorium following the Earthquake caused by the shale gas exploration well drilled by Cuadrilla near to Blackpool [19].

BritGeothermal

Figure 14 The distinctive BritGeothermal logo as used for the research grouping of Newcastle, Durham and Glasgow universities with the British geological Survey between 2012 and 2019.

BritGeothermal also led the organisation of the London Geothermal Symposium from 2014 until 2019. The first symposium in this series was organised in 2011 by EGS Ltd with a handful of people meeting at the Institute of Directors in London on 27th September 2011. Paul and the other members of BritGeothermal were present. By 2012 the symposium had moved to the Geological Society's Burlington House, Piccadilly and numbers in attendance had doubled. After assuming leadership of the event, it became a major aspect of BritGeothermal's existence and Paul a major player in the event organising and attending each one until his last in 2015. For anyone working geothermal this event is the most important one in the UK each autumn.

BritGeothermal was successful at promoting the case for geothermal energy in the UK, but it did not live up to the expectations of its founders in terms of research co-operation and progress. It did not act collectively to win research funding. In part that was caused by the structures within the three university partners and BGS, each tending to do their own thing. The group did however come together to produce what was probably Paul's last paper, 'Keeping warm: a review of deep geothermal potential of the UK' [20]. It was published just before Paul's death. He contributed to the original idea but was already poorly as it went for review.

6. Paul's publications on geothermal energy

Paul's first publications on geothermal heat are all associated with the Eastgate borehole, but it is clear from other works which include references to heat injected into subsurface mine water [21] that he had begun to think about the thermal characteristics of subsurface water before embarking upon the quest to drill at Eastgate. As for Eastgate, we are fortunate that possibly the first report ever produced by Paul, whilst not a peer reviewed volume is available on the Durham County Council website [20]. The report, completed soon after the drilling phase of the well was complete details the time/depth drilling curve for the well (Figure 15) as well as noting the likely bottom hole equilibrated temperature, provisionally given as 48 °C at 1000 m and speculating that a well drilled nearby to a "production" depth (the quotes are used but not explained in the report) would deliver at 78 °C or thereabouts.

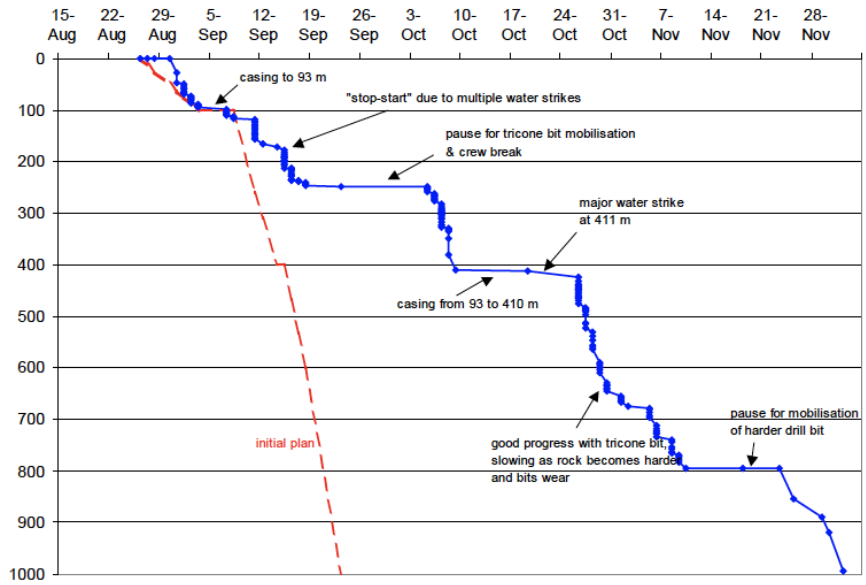

Figure 15 Eastgate well time depth plot for drilling the well. Note the annotations on water strikes in the well (from Dufton et al 2004 [22]).

The oldest formal publication we have found on Eastgate is not by Paul but is a one-line mention of the well by the other great and unfortunately late supporter of geothermal energy in the UK Tony Batchelor in a report to the World Geothermal Congress in 2005 [23]. Tony Batchelor was the main driver behind the hot dry rock project in Cornwall in the 1980s [24] and thus forerunner to the recently executed Eden and United Downs geothermal schemes [25].

The Eastgate borehole's completion began a suite of publications from Paul and co-workers [26–31]. The Eastgate experience opened up a whole new research line for Paul on geothermal energy with a wide geographic spread from Shetland to East Africa and an array of different topics from shallow urban heat systems to the deep and hot granite and saline aquifers as well as instrumentation and technology papers [8,14,30,32–46]. Paul took one step further than simply publishing on geothermal systems, he helped set up Cluff Geothermal Limited (later named Hotspur geothermal Ltd) [47], a company that explored for geothermal energy in the UK and East Africa.

The final paper written by Paul on geothermal energy was on the Science Central borehole in Newcastle [14]. The paper was originally submitted in the late spring of 2016 to the Journal of the Geological Society but much to Paul's dismay and anger was returned withing 24 hours and deemed too parochial for the journal. The paper was resubmitted to the sister journal Quarterly Journal of Engineering Geology soon thereafter and a few days later Paul left for holiday in France. It was whilst on holiday that Paul first recognised that he was poorly when one morning he found he was unable to say the words he wanted to speak. He returned to the UK and later learned of the full extent of his brain tumour. The paper was retuned for corrections. Paul was not able to do them and passed responsibility to me (JGG). That was unfortunately the final correspondence I had with him. The paper, 90%+ of which was written by Paul, was accepted for publication in September 2016.

7. Paul's legacy

Perhaps the most tangible sign of Paul's geothermal legacy is that in death he has returned to his birthplace in Hebburn, commemorated as the Paul Younger Energy Centre which since November 2023 has been providing low-carbon heat to buildings and residents in the town. The system uses heat pumps, some of which extract heat from abandoned and flooded underground coal mine workings to reduce the reliance of the local South Tyneside Council on gas fired boilers. The council calculates that use of the low-grade heat has led to a saving of 320 tonnes of carbon dioxide emissions each year [48].

The UK Geothermal Centre was founded as a not-for-profit company limited by guarantee in January 2024 and formally launched at Dynamic Earth Edinburgh on 13th June 2024. The founding partners are Durham University (Durham Energy Institute), the Net Zero Technology Centre (Aberdeen) and Aberdeen based not-for-profit company Shift Geothermal Ltd with funding from these partners and the Reece Foundation. The centre's aim is to promote and facilitate the development of the UK geothermal industry to help deliver sustainable secure and ultimately equitable geothermal energy for the UK. Although it was conceived during discussions on video calls during the Covid lockdowns of 2020, well after Paul had died, its very existence is born out of Paul's vision for a cleaner energy future in which geothermal plays a key part.

The quest to develop an eco-village at Eastgate in Weardale, heated by geothermal water from the wells, seemed to be permanently lost when the Lafarge site was sold by Durham County Council to a private investor, but that was not so. Eastgate Ecopark Ltd was incorporated on 3rd March 2015 and sister company Weardale Lithium Ltd in 2020. The plans now for the area include both heat and lithium extraction from the Weardale Granite Paul and co-researchers identified the presence of lithium in the water flowed from Eastgate 1 [26] whilst Gluyas *et al.* [49] suggested that the concentration at 100 ppm was likely to be extractable economically.

8. Co-workers and research students

Paul supervised many students and had many co-workers during his time at Newcastle and Glasgow universities. We asked a few of them to describe their perceptions of legacy from knowing and being supported by Paul.

Aislinn Williams: Paul came into my life at a point in time when I was at my lowest and despite the challenges that presented him, he was still one of the strongest, warmest and most considerate people toward me. Paul was the kind of person who wanted the best for anyone, as far as I saw – even when that meant putting himself in the line of fire. For me, a testament to his character was in his love of going to care homes to entertain some of the most needy folk, by playing his guitar and singing his seemingly endless list of songs. This character extended to his career where he applied his love of geology to build a better future for everybody, attempting to address energy poverty, one of the more prominent issues in our society. I found a connection with Paul through a shared love of collecting fossils and minerals, particularly fluorite from the old lead mines in Weardale. It was through Paul that I learned that my own love of geology is through finding the parts of earth which I find beautiful, like those minerals. Paul is the inspiration in my own attempt to build a better world.

Cat Hirst: My first encounter with Paul was in 2012 whilst I was completing an MSc Engineering Geology degree at Newcastle University. Paul delivered a lecture on geothermal energy as part of the course, and that's all it took to ignite my own interest and passion in this field of study. His infectious enthusiasm and rich knowledge of the subject meant the lecture didn't feel like a lecture at all. His way of communicating science could have made the dryest of topics engaging, and without wanting to sound too dramatic, Paul literally changed the course of my career with that one lecture. He was someone who was always in demand due to his wide-ranging knowledge in geology, hydrogeology, geothermal energy systems and mine water pollution, yet he still managed to connect with so many people from a wide cross section of society.

Without Paul, I don’t think the UK geothermal industry would be where it is today. Seeing his research summarised in this manner reminds us of the legacy he left us all. May it serve as a reminder to continue building upon his work, pushing towards a greener more sustainable future.

Charlotte Adams: I first met Paul during an interview for my PhD in 1996 this was successful, and I joined the Civil Engineering Department at Newcastle University that autumn. Paul was and enthusiastic and vibrant supervisor immediately welcoming me to the department and introducing me to colleagues. I was amazed to learn the extent of his skills, he was a gifted musician, poet and writer, linguist but above all a devoted family man. His sharp wit, eloquent turn of phrase and sense of humour was second to none and it was a pleasure to have him supervise my research.

We worked on zinc removal from circumneutral mine waters, zinc being highly toxic to fish and invertebrates living in the water courses that received the mine water discharges. As part of that research, we spent time exploring underground and often crawling through tight, wet spaces in the disused lead zinc mines of the North Pennine Orefield in our orange boiler suits. Observing and sampling the secondary minerals growing within the mine got us thinking that we if could recreate this within our treatment system we could provide a low cost/passive means of mine water treatment. Lab and field trials ensued, and Paul was quick to volunteer to help me shovel 4 tonnes of limestone gravel into a large plastic bag that was my research reactor. Results were promising and I’m delighted that our research was adopted by the Coal Authority at one of their metal mine treatment systems in the North Pennines.

I was lucky to share in numerous celebrations of Paul’s excellence and achievement including the creation of our “HERO” research group, the Queens Anniversary prize and his promotion to Professor. I was delighted to continue to work with him throughout my subsequent career as we both explored geothermal opportunities, he leaves an immense legacy in both mine water treatment and geothermal and we owe much of the progress we see today to Paul. Paul is missed and remembered fondly regularly by all of us but he lives on through all that he achieved and the countless people that he inspired.

Helen Robinson: I met Paul in 2012 at a conference that back then did not have any geothermal included in its program. I was there to present some research I had completed on gabbro’s which happened to be Paul’s favourite rock type. We quickly hit it off and got onto the subject of geothermal, which happened to be the direction I wanted to go in. Despite still having 18 months left of my undergraduate degree, Paul asked if I would be interested in joining him in Glasgow for a PhD opportunity studying geothermal in Kenya. On completion of my undergraduate degree, I reached out to discover there were still opportunities available. And so, my journey began.

I was excited and a little nervous moving from Devon all the way to Scotland, but Paul was quick to get me settled into Glasgow and PhD life. Paul was an impressive, funny, larger than life character; from the incredible knowledge covering so many different subjects, opening his Inaugural Lecture as Rankine Chair of Engineering at the University of Glasgow by singing about the northeast coal industry in Gaelic, and his love of his Christmas jumper with flashing lights. Importantly for me and his students, he was approachable. His door was always open, he was clear and concise in guidance, he believed in me, and he empowered me to be the best version of myself. Occasionally I still find myself wondering what he would say or do in a certain situation. It was an absolute privilege to have worked with him. He may have been my supervisor, but he was also my friend.

Sean Watson: In 2015, my grandpa and I joined the 200,00 strong crowd at the Durham Miner's Gala. On this occasion we had the immense privilege and pleasure of walking with Professor Paul Younger, and his family and friends, under the Harraton ('Cotia) Pit Banner, and experienced them heartily belting out 'A Miner's Life' in front of the County Hotel. They are memories I'll never forget.

Paul had an infectious enthusiasm, passion, and commitment to work for the better of society and the environment, and being in Paul's company, whether that was during 'The Big Meeting' or a PhD supervisory meeting, was inspiring.

Paul inspired me to complete my undergraduate dissertation on 'The Scope for Deep Geothermal Energy to Alleviate Fuel Poverty in the East End of Glasgow' and then PhD thesis on 'An Investigation of the Geothermal Potential of the Upper Devonian Sandstones Beneath Eastern Glasgow', and continues to inspire me both in work, and in life. It was a privilege to have had the opportunity to be supervised by him, and to have known him.

'Cotia was the colliery, her men were true and bold'.

9. Conclusions

Paul Younger was a geologist born and bred in the NE of England died in 2016 leaving a legacy of substantial proportions. He drilled three deep geothermal wells in the NE England at a time when the potential was simply ignored by many. His vision was to use low enthalpy geothermal energy to displace fossil fuels as a source of heat for buildings. That vison has begun to be realised. The UK now has several new geothermal systems operational and many more in the pipeline. Many of those folk who are today delivering low-carbon geothermal heat and helping displace fossil fuels, worked with or for Paul in the two decades before his untimely death in 2018.

Competing interests

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This paper would not have been possible in the form presented without inputs from former students and co-workers of Paul Younger. On this occasion rather than acknowledge their contribution to the paper here, you can read their contributions verbatim as the describe the personal legacies they have from Paul Younger.

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