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Awards Ceremony Speech

Citation for the 2018 C.C. Patterson Award to Sigurdur R. Gislason

It is my honor to introduce Sigurdur 'Siggi' Reynir GISLASON, of the University of Iceland for the Patterson Medal in Environmental Geochemistry of the Geochemical Society. Few if any scientists have neither addressed nor have made as large a contribution to resolving environmental issues as Siggi. His major contributions have fallen into three broad categories: Carbon Capture and Storage (CCS), volcanic hazards, and how natural processes affect climate at a global scale as I will detail below.

Siggi first got involved with carbon capture and storage, in 2006 when he was contacted by Olafur Grimsson, the Icelandic President, to devise an Icelandic solution to CCS. This request rapidly evolved into the CarbFix project, a collaboration between Siggi, Wally Broecker (Columbia University), Reykjavik Energy, and myself to design and demonstrate the viability of capturing and storing anthropogenic CO_2 as stable carbonate minerals through its reaction with basaltic rocks. Over the course of the past decade, Siggi has worked in close collaboration with geothermal energy companies, engineering companies, the Ministry for the Environment and a suite of Icelandic and international scientists to design the injection system, characterise the subsurface geology/hydrology, define the optimal injection conditions, and develop an extensive monitoring strategies. The challenge to put together and complete a large-scale environmental field project such as this is huge, not even counting the efforts required to get permission to inject carbon as radioactive tracers into the subsurface. Finally in 2012 after years of background work, CO_2 began to be injected into the subsurface and has been highly successful. Using a suite of novel and reactive and conservative tracers CarbFix demonstrated the conversion of more than 95% of the injected CO_2 into stable calcite in less than two years at 20–50 °C, providing safe and efficient mineral storage of anthropogenic carbon. This is the first pilot- and industrial-scale demonstration of mineral carbonation. The success of this project has received worldwide attention since the publication of its major findings in an article published in Science magazine (Matter et al., 2016).

The research within the CarbFix project continues at present. Siggi, leading the CarbFix collaboration has developed new technology to co-inject CO_2 with mixed-acid gases that both provides safe storage for toxic gases such as H_2S, and also has lowered considerably the costs of the overall CCS process (to approximately $30/ton CO_2 captured and stored). As such, this method has now been adopted as routine at the Hellisheidi geothermal power plant, the largest in Europe, and deployment is planned at other power plants.

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In some ways, the community may have underestimated Siggi's role in the CarbFix project as he is commonly neither the first, second, nor even last author on many of the papers reporting the various results from the CarbFix project. This is due to his personal generosity; he always places students, post-docs and junior faculty in more prominent positions on author list to help promote their careers, at times underselling greatly his contribution and leadership in the project.

Fig. 1. Siggi in the field during the 2010 Eyjafjallajökull eruption.

Although just Siggi's successful demonstration of carbon mineral storage in less than 2 years at the industrial scale, merits the Patterson medal all on its own, as it testifies to our ability to use geochemistry to tackle the global carbon challenge, Siggi could also be awarded the Patterson medal in recognition of his success in characterising, quantifying and better understanding volcanic hazards or his contribution to demonstrating how Earth surface processes influence global warming.

Siggi's contributions towards understanding the effects of volcanic hazards are vast, ranging from defining potential toxic gas and metal transport to working directly with Icelandic Department of Civil Protection and Emergency Management to help evacuate people from affected areas. I feel that two of his contributions are particularly noteworthy. First, Siggi was the first scientist to collect fresh volcanic ash from the explosive 2010 Eyjafjallajökull volcanic eruption; the eruption that shutdown air traffic over most of Europe for a week. Siggi drove into a nearly completely dark ash cloud at much personal risk to collect these samples. Siggi, together with collaborators at the NanoGeoScience Center in Copenhagen and University of Iceland, developed a protocol to assess the risk to air traffic and pollution of this volcanic ash. A summary of this work was published by Siggi with 12 co-authors in the Proceedings of the National Academy of Sciences in 2011 (Gislason et al., 2011). Siggi's second major contribution

Fig. 2. Siggi sampling on the Skaftá River, November 2006.

Fig. 3. Siggi filtering river water samples, September, 2002.

Fig. 4. Siggi sampling fresh volcanic ash from the 2010 Eyjafjallajökull volcanic eruption at April 15th at 12:01. Photo Ómar Óskarsson.

Fig. 5. Siggi driving to sample ash from the flank eruption of the Eyjafjallajökull volcano, March 2010.

Fig. 6. Siggi explaining the CarbFix CO_2-H_2S injection system, June 2016.

to understanding volcanic hazards determined and quantified the distribution and potential consequences of toxic gases, notably SO_2 from the 2014–2015 Bardarbunga eruption, aiding in our understanding of how to better protect the population from these toxic gases as reported in Gislason et al. (2015).

Siggi has also made major contributions to our understanding of how Earth surface geochemistry influences the global carbon cycle and ultimate global temperature. In a series of highly influential studies, Siggi with students and co-workers were the first to demonstrate and quantify the direct link between increasing Earth surface temperature, increased weathering rates of Ca-Mg-silicates, and CO_2 drawdown in a study spanning over nearly 40 years, and generating over 200,000 individual data points – including the daily weathering fluxes of 8 Icelandic river catchments (Gislason et al., 2009).

What is perhaps most impressive about Siggi is his broad skill set to approaching each and every subject. He is equally skilled in performing detailed field work, precise experiments and geochemical modelling. Some photos of Siggi in his various modes are shown in Figs. 1–8. It is though the combination of these complimentary skills that he has been able to make such large advances in Environmental geochemistry.

Fig. 7. Siggi working on plug flow experiments with Didre Clark, September 2017.

Fig. 8. Siggi discussing results of CarbFix injection while in Tuscany with Fidel Grandia, Edda Aradottir, Ingvi Gunnarsson, and Eric Oelkers during March 2017.

I hope and anticipate that Siggi's successful application of the fundamentals of geochemistry towards solving major global challenges inspires numerous other scientists to use their skills to continue making the world safer and more sustainable.

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Awards Ceremony Speech

Acceptance of the 2018 C.C. Patterson Award to Sigurdur R. Gislason

Dear friends and colleagues.

I would like to thank the Geochemical Society and you, President Roberta Rudnick, members of the Patterson Award Committee, my colleagues who nominated me for this award and especially my friend and close collaborator for the last 25 years, Eric Oelkers, for his citation.

It is difficult to express my feeling on receiving of this prestigious reward; pride, humility and gratitude to my family, teachers, collaborators, graduate students and post-docs who have inspired, challenged and entertained me throughout my career. My humility stems, in part, from receiving an award named after one of the most distinguished environmental geochemists of the past century, Clair C. Patterson.

Now - how did I get here? As a young boy, I spent summers at my grandfather's farm in southeast Iceland, downstream from the Katla volcano. In the evenings, I would listen to stories of eruptions, ash falls and my grandfather galloping on his horse in front of the glacier's outburst flood associated with the 1918 eruption of the Katla volcano. At the peak of the flood, it was the largest river on Earth. My interest in volcanoes and geology was kindled.

My high-school teacher Halldor Kjartansson further inspired me to go for geology at the University of Iceland. There I learned from Stefan Arnorsson and Sigurdur Steinthorsson the power of thermodynamics, and how it helps to interpret water-rock interactions. After graduation in the spring of 1980, I took my first job as a geologist at the Nordic Volcanological Institute before heading to Johns Hopkins University for graduate school that fall. And boy did I get lucky, during that summer Hal Helgeson visited and there were two volcanic eruptions. I thought Hal was great, fun, incredibly smart and liked to party into the early morning. I was sure at that time that he was a typical US professor and I was eager to meet more of them.

I spent my last week in Iceland on the slopes of the erupting Hekla volcano before my departure for the US in late August 1980. I took one day to pack, and received a culture shock when I arrived for the first time in New York and then onwards to Baltimore. There I was to study gas buffers in basaltic geothermal systems with Hans Eugster at Johns Hopkins University. Hans was a great mentor, scientist, teacher and artist. We had Friday seminars at his farm in Western-Maryland, where his wife Elaine, a professor of mathematics at Goucher College, would cook wonderful dinners for us, served on Hans' handmade pottery. At the table, we were also surrounded by his paintings. I was a teaching assistant for Hans' thermodynamic classes. He would always get nervous; he put all his energy into them, and his writing and drawings on the blackboard were spectacular. Later when I asked him about it, he said that he always got nervous before his classes and talks, - "and when you stop being nervous, it is time to quit".

For my PhD-thesis, I did field and laboratory studies of meteoric water-basalt interactions with Hans (Gislason and Eugster, 1987a,b). I had a few post-doc options in USA and Canada at the end of my thesis in 1985, but my wife Malla, an architect and urban planner, received an excellent offer from an Icelandic architectural firm, so I followed her back to Iceland and started on a soft money post at the University of Iceland. I went back to Hopkins on a Fulbright Fellowship for a few months in 1987, working with Dave Veblen on a TEM study of alteration products created during my low temperature PhD experiments (Gislason et al., 1993). At the end of our stay at Hopkins in early autumn, we drove to Martha's Vineyard where Hans and Elaine were building a summerhouse. We did some carpentry in the morning and walked along the beaches in the late afternoons. When we left on the ferry, Hans waved for a long time, which was unusual for him. This was the last time I saw him, he died two months later from an infection, at the age of 62, virtually with his boots on.

Hopkins was a powerhouse in the 1980′s. In "Hans' group" were Eugene Ilton, Glenn Wilson, Ron Spencer, and Tim Lowenstein and in "Dave's group" there were Ken Livi, Peter Heaney, George Guthrie, Jill Banfield among others. Kathy Cashman became my volcano-friend and Andy Jephcoat was always there, if he was not tending his diamond-cell at the Geophysical Laboratory in Washington. Hans' students had a very important connection to the US-Geological Survey in Reston, Virginia through Blair Jones, an inspiring and generous friend and scientist.

In 1994, I went on a Sabbatical to Toulouse, France, with Malla and our eight-month-old twins, Anna and Birnir, to work with Jacques Schott conducting dissolution kinetics experiments on moganite (a novel silica polymorph) and quartz. Peter Heaney, a Hopkins friend, had recently shown

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that chalcedony and chert specimens from around the world contained moganite. Chalcedony generally contains between 5 and 15 wt% moganite, whereas chert from evaporitic environments may include more than 50 wt% moganite. We wanted to define moganite's dissolution rates and thermodynamic properties (Gislason et al., 1997). On my first visit to the lab in Toulouse I ran into Eric Oelkers. And what an impact, - it was "Helgesonian". Eric was and is direct, brilliant, honest, trustworthy and a lot of fun. We have been the very best of friends and collaborators from that day. My family and I were a frequent visitor to Toulouse over the next 15 years and enjoyed the hospitality of Eric, Stacey and Jacques. With PhD students and postdocs, we quantified the dissolution rate and dissolution mechanism of volcanic glasses (Oelkers and Gislason, 2001; Gislason and Oelkers, 2003; Wolff-Boenisch et al., 2004a,b), climate control of weathering of basaltic rocks (Gislason et al., 2009), the role of river suspended material in the carbon cycle (Gislason et al., 2006) and the effect of crystallinity on dissolution rates and CO_2 consumption capacity of silicates (Wolff-Boenisch et al., 2006). The tide changed in 2007 with the beginning of the CarbFix project in Iceland.

In February 2005 the Kyoto protocol entered into full force committing countries to limit CO_2 emission. To address this challenge, the Icelandic President approached Einar Gunnlaugsson at Reykjavik Energy, Iceland, Wally Broecker at Columbia University, USA, Eric Oelkers at CNRS Toulouse, France and myself at the University of Iceland to design a project, later referred to as CarbFix, to aid in limiting greenhouse gas emissions in Iceland. After nearly a decade of experiments, obtaining permissions and the preliminary injections, Reykjavik Energy and other members of CarbFix laid the foundation of industrial scale gas capture and injection at the Hellisheidi site (Gislason and Oelkers, 2014; Gislason et al., 2018; Sigfusson et al., 2018). We demonstrated the rapid mineralization of injected CO_2 and H_2S in 2014 (Matter et al., 2016; Snæbjörnsdottir et al., 2017), which has now been upscaled to an industrial process where a $CO_2 + H_2S$ mixture is being captured directly in a water scrubbing tower that was built next to Hellisheidi geothermal power plant, injected into the ground, and mineralized within months (Sigfusson et al., 2018). Already this is both making geothermal energy cleaner and saving the electricity consumers in Reykjavik millions of dollars per year. We are currently working on upscaling this process to capture and store far larger quantities of CO_2 below the seafloor, by first using seawater to capture CO_2.

The CarbFix success has been a joint effort by many collaborators and students including: Kristjan Guy Burgess and Örnolfur Thorsson from the President's Office, Wally Broecker, Klaus Lachner, Juerg Matter and Martin Stute from Columbia University; Eric Oelkers and Chiara Marieni from CNRS Toulouse France; Einar Gunnlaugsson, Grimur Björnsson, Thorleifur Finnsson, Holmfridur Sigurdardottir, Eirikur Hjalmarsson, Edda Sveinsdottir, Ingvi Gunnarsson, Edda Aradottir, Bergur Sigfusson, Trausti Kristinsson and Einar Thrastarson from Reykjavik Energy; Domenik Wolff-Boenish, Andri Stefansson, Eydis Eiriksdottir, Martin Voigt and Thorsteinn Jonsson from the University of Iceland; Gudni Axelsson, Thrainn Fridriksson, Vigdis Hardardottir, Hjalti Franzson and Björn Hardarson from the Icelandic GeoSurvey; Teitur Gunnarsson and Magnus Arnarsson from Mannvit Engineering; Susan Stipp and Knud Dideriksen from the University of Copenhagen; Jordi Bruno and Fidel Grandia from Amphos 21 Barcelona; and finally Benedicte Menez, Rosalia Trias, Emmanuelle Gerard and Paul le Campion from the microbiological group from various parts of France. From 2007 the CarbFix PhD-students have been: Therese Flaathen, Alexander Gysi, Edda Sif Aradottir, Gabrielle Stockmann, Iwona Galeczka, Snorri Gudbrandsson, Jonas Olsson, Helgi Alfredsson, Sandra Snæbjörnsdottir, Jan Prikryl, Deirdre Clark and the MSc-students; Mahnaz Khalilabad, Diana Fernandez de la Reguera, Elisabet Ragnheidardottir and Kiflom Mesfin. Most of the students studied at the University of Iceland and many of them hold a joint degree between the CarbFix University partners.

In the meantime - being in Iceland, we "are blessed" with natural disasters! One of the 30 active volcanoes erupt on average every 3–5 years. Many of them are covered with glaciers causing magma fragmentation, volcanic ash formation and outburst floods when they erupt. When a volcanic plume comes out of the eruption conduit, its temperature is higher than 800 °C. It can rise in a short time to more than 10,000 m in height, where the ambient temperature is around minus 50 °C. During this ascent and cooling, some gases, acids and volatile metals condense as soluble salts on the ash surfaces and/or form aerosol salts. We have shown that the volcanic gas, ash and metal- and acid-aerosol salts can both fertilize and harm the environment (Frogner et al., 2001, 2006; Gislason et al., 2002; Jones and Gislason, 2008; Olsson et al., 2013; Galeczka et al., 2017). The impact is dependent on the composition of the magma, size of the eruption, eruption rate and the eruption mechanism; explosive versus hydro-magmatic (Gislason et al., 2011; Olsson et al., 2013). The impact is also time and location dependent. At high latitudes during midwinter, when there is limited light and high wind speeds, the impact is different than that at midsummer with near 24 h of light and low wind speed (Flaathen and Gislason, 2007; Gíslason et al., 2015).

These studies have been exciting. I have seen the beauty and terror of nature at its extreme, in the company of my students, postdocs and collaborators. To name few they include Stefan Arnorsson, Niels Oskarsson, Ingvi Gunnarsson, Andri Stefansson, Arni Snorrason, Hrefna Kristmannsdottir, Arny Sveinbjörnsdottir, Peter Torssander, Silvie Castete, Bernard Dupre, Paul Kockum-Frogner, Morgan Jones, Bergur Sigfusson, Jorunn Hardardottir, Gunnar Sigurdsson, Vilhjalmur Kjartansson, Hakon Adalsteinsson, Therese Flaathen, Eydis Eiriksdottir, Eric Oelkers, Helgi Alfredsson, Kevin Burton, Philip Von Strandmann, Sophie Opfergelt, Susan Stipp, Tue Hassenkam, Sorin Nedel, Nicolas Bovet, Caroline Hem, Zsuzsanna Bruns-Balogh, Knud Dideriksen, Gudrun Larsen, Jonas Olssen, Kim Dalby, Emil Makovickyc, Iwona Galeczka, Thorsteinn Jonsson, Hlynur Skagfjörd Palsson, Gerdur Stefansdottir, Melissa Pfeffer, Sara Barsotti, Thorsteinn Johannsson, Eniko Bali, Olgeir Sigmarsson, Nicole S. Keller, Arni Sigurdsson, Baldur H. Bergsson, Bo Galle, Valdimir Jacobo, Santiego Arellan, Alessandro Aiuppa, Elin Jonasdottir, Sigurdur Jakobsson, Gudmundur Gudfinnsson, Sæmundur Halldorsson, Haraldur Gunnarsson, Babtiste Haddadi, Ingibjörg Jonsdottir, Thorvaldur Thordarson, Morten Riishuus, Thordis Högnadottir, Tobias Dürig, Gro B. M. Pedersen, Armann Höskuldsson, Magnus Gudmundsson, Katherine Cashman, Emma Liu, Alison Rust, Finnur Palsson, Stefanie Lutz, Liane Benning, Rikey Kjartansdottir, Johann Gunnarsson-Robin, Shuhei Ono, Rosa Olafsdottir, Nicole S. Keller, Svava Thorlaksdottir and Sibylle von Löwis.

The key when receiving an honour like the Patterson Award, however, is to look forward rather than look backward. Mankind faces a number of large challenges from global warming to new environmental hazards. The world looks to scientists such as ourselves to help solve some of these problems. I hope that my past work has helped a bit in this effort and I am looking forward to continue to contribute in the coming years. Thank you very much for your attention.

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