Data Echoes: Sound, Evidence, and Acoustic Methods in Energy Landscapes

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Abstract

This paper explores an informal acoustic method developed by a group of industrial geologists working in geothermal energy landscapes in the southwest of Iceland. Through a series of ethnographic descriptions, the paper renders the work these geologists carry out in sonic terms, emphasizing how they use their bodies as sonic detectors in the production of geological evidence. Sound, the paper argues, is what allows geologists to make the intractable problem of volcanic cooling doable. It does this by differentiating two forms of evidence. Primary evidence, which ends up as data in geological reports, and secondary sonic evidence, which is what establishes that this primary evidence is, in fact, evidence. The paper introduces the concept *data echoes* as a way to think about how sound articulates between these evidential protocols. As echo, sound works as an outside, which, while remaining external to official protocols of knowledge production, nevertheless helps to constitute distinctions that are meaningful to the production of those categories. As data echoes through the various moments of data capture, analysis, and model building, sound's temporal form helps to predict the timeframe of volcanic cooling, as it affects both the immediate energy production scenarios, and the long durée of volcanic time.

Keywords: sonic articulations, evidence, data echo, energy, acoustic methods

1. Introduction

In *Memory Practices in the Sciences* (2005) Geoff Bowker introduces us to the acclaimed geologist Charles Lyell. For Lyell, the myriad features of the earth were not only instances of geological processes; they were also a way for the earth to keep records of itself. Breaking with previous geological traditions, Lyell suggested that the earth formed its own— somewhat inefficient— archive. As a poor archivist, the earth needed a mediator to supplement its deficiencies. This mediator came in the guise of the geologist; the "man" of science who documented the traces left by the earth in the production of geological knowledge. Documenting such traces became central to how geological theory developed over time and continues to be an important part of the practical suite of methods used by geologists today.

This paper takes us to Iceland, a place where tectonic activity overflows and envelops the landscape. Eruptive fissures, spewing geysers, mossy green lava flows, and expansive glaciers are common sights that ignite the curiosity of those who live and travel there. Many geologists are drawn to this volcanic island as a site for theorizing about plate tectonics (Oslund 2011, 41-45). Tourists are also drawn there as a geological mecca, of sorts. These turbulent landscapes situate the story to follow. Based on one year's fieldwork in southwest Iceland during 2013 and 2014, this paper follows the tracing practices of a small group of industrial geologists working for a municipal geothermal energy company. The company, Reykjavík Energy, has been extracting vast quantities of geothermal steam and water from deep within the subterranean of the Hengill volcanic zone since 2012 to provide electricity for Century Aluminum, a large multinational aluminum concern.

Extracting steam to produce electricity is a form of volcanic terraforming. Despite being Iceland's most continuously active earthquake zone (Foulger and Toomey 1989), over fifty wells have been drilled 3 kilometers deep into Hengill's subterranean zone, extending over vast quadrants of the landscape. While geothermal fluids exist in an intensely pressurized form deep within underground rock fractures, bringing them up to the surface involves calibrating relations between the underground and overground—in particular heat and pressure relations—to maximum acceleration effect. Moving through underground chambers, fluids accelerate as they heat up, exploding upwards through the extraction technologies, and transitioning from fluids into steam. Producing electricity for aluminum is a process of geological acceleration; configuring the landscape to transform water from its liquid phase into steam to supply Century Aluminum's smelters with 24/7 power.

But these accelerations had strange effects as energy output continued to decline over the course of my stay in Iceland. At the heart of this was a concern that the speed and scale of subterranean extraction might be cooling some of the remnant heat in the subterranean volcanic mass. The industrial geologists with whom I conducted fieldwork were consumed with this cooling issue. Their method for approaching the problem was called a tracer test; an experimental attempt to trace, describe, and model the fracture pathways and flow patterns of the subterranean arteries of the geothermal reservoir. The purpose was to assess whether and how extractive operations were contributing to cooling various parts of the volcanic area.[i] A clear indication of volcanic cooling posed a serious financial threat not only to the municipal entity, but also to the entire city of Reykjavík. Additionally, it would put a stop to any future energy extraction from such active seismic areas, halting the government's plans for a much sought-after energy boon to an economy still faltering from the wreckages of the 2008 financial crisis.

The volcanic and earthquake prone landscapes in which these industrial geologists operate are fractured and turbulent. Continuous earthquake activity cyclically re-writes the topography of the area and produces the conditions that make possible voluminous geothermal extraction (steam and water). At the same time, this variability intensifies the difficulties of working within this landscape and it often triggers the need for more ad hoc approaches. Tracing—which will be explained below—is one approach that these geologists have designed in response to the shifting nature of the landscape and the resources opportunities, and difficulties, that are generated within it. This paper will explore how these industrial geologists make this intractable problem "doable"—in Joan Fujimura's (1987) sense of the term—by means of a tacit, informal set of acoustic methods that relies on their bodies and senses as instruments in producing evidence. Through a series of ethnographic descriptions, the paper will demonstrate that the evidential culture of these geologists operates through a *double articulation*, as primary evidence is shown to be dependent upon a sonic layering that resides within it. The paper thus explores how sound articulates the gaps within and between evidential protocols, introducing the term *data echoes* as a way of conceptualizing these gaps.

2. Articulating Sound as Evidence

The study of sound as a means of apprehending culture has a long history in anthropology, from Franz Boas's pioneering study of "sound-blindness" (1889) to the interrelationship between myth and music in Claude Levi Strauss' *The Raw and the Cooked (1969)*. More contemporary work from Steven Feld and others has positioned sound as a legitimate, though difficult, object of investigation (2021). As a nascent and burgeoning interdisciplinary field, Sound Studies works from these lineages and publishes a broad palette of research that takes sound as its primary empirical and analytical object (Sterne 2012; Novak and Sakakeeny 2015; Schulze 2021). STS's contribution to this field has been slowly growing. Prior to Edward Yoxen's work—which I will come to a little later in this section—Trevor Pinch and Karin Bijsterveld (2004) have come to sound by way of music technologies, emphasizing STS's ability to contribute to the "materiality of sound, its embeddedness not only in history and society, and culture, but also in science and technology and its machines and ways of knowing" (ibid : 636). However, much of the subsequent work has retained this focus on the role of sound technologies, and there is little by way of thinking about sound's role in the production of scientific knowledge.

While it is well understood that individual scientists bring their own subjectivities to research processes, the role of the sensory in scientific knowledge production is less researched, although there are some notable examples of important work (Hustak and Myers 2012; Myers 2009; O'Reilly 2016; Skrydstrup 2017; Yoxen 1987). These scholars pave the way for thinking about the sensory work that geologists conduct in the volcanic landscape, and how this work is important in evidence and knowledge production. Of more particular relevance for this paper is Stefan Helmreich's (Helmreich 2013; Helmreich 2016a; Helmreich 2007; Helmreich 2015) extensive work on sound. In Gravity's Reverb:Articulating the Sounds of Gravitational Wave Detection, Helmreich (2016) develops the concept of "articulation," taking his point of departure from an event in which US-based astronomers at the Laser Interferometer Gravitational Wave Observatory (LIGO) announced that they had detected gravitational waves, vibrations in the substance of space-time. When they made the detection public, the scientists had translated the signal into a sound, a "chirp," a sound wave swooping up in frequency, indexing, scientists said, the collision of two black holes 1.3 billion years ago. While gravitational-wave phenomena are not acoustic, translating them into sound can aid in judging a signal's significance. While the data can also be read visually on graphs, listening to them adds another dimension; "the ears pick up what the eye sometimes misses" (2016b: 479).

The LIGO detector is a massive device distributed across two physical sites and is constantly vibrating owing to seismic, ambient, and quantum fluctuations. For signals to be discerned at all (by machines or people) the ambient noise or hums of the detector have to be controlled or held steady. To make sense of the data, scientists need to develop an "articulate form of listening."[ii] Listening is a learned process, which gives, as Helmreich puts it, "a sense that something is happening." Listening for the pattern of the detectors thumps and bumps as it goes through various types of transitions is what allows these scientists to diagnose the performance. "Once noises are stabilized it becomes possible to detect a signal" (ibid : 482). Articulate listening, for this group of scientists, is an acoustic method that helps them to "make sense and sensibility from signals" (ibid : 479).

While this group of astrophysicists set their ears, and instruments, towards the cosmos, the industrial geologists at Hengill turn their ears towards the earth and the various technologies of extraction assembled upon it. Both have developed an articulate form of listening that helps them make certain sound distinctions in order to generate meaningful evidence and data. For Helmreich's scientists, transitions in the detection equipment are part of what's important. The foci for this geology team are the moments when fluids transition into the gaseous phase as they accelerate and roar out of the earth and into geothermal wells.

For Helmreich such articulations provide an entry point for conceptualizing how sound is translated and linked through various entities (astrophysics as a discipline, the LIGO detector, computer algorithms, and the scientists). Thus, Helmreich suggests that gravitational-wave sounds emerge from semiotically and technologically specific articulations of humans with machines and nonhuman phenomena (ibid : 467).

This notion of articulation sits in the background of the ethnographic descriptions and argument that I present. On the one hand, I will give a sense of the variations in the type and intensity of sounds that emerge as subterranean fluids work their way up through the apparatus of extraction: rumbling, guttural, screeching, roaring, pulsating. On the other, I also characterize these sounds as particular *articulations* that emerge through the connections between earth processes, technologies of extraction, and the humans working with them. As we shall see, a whole range sensory affects are implicated in the articulation of sound *as a distinctive form of meaningful evidence*.

Conventionally, evidence has been regarded as the basis upon which a claim (or hypothesis) is justified, believed, or said to be true (Kelly 2016). But just what that basis is, or is understood to be, shows considerable variation. The epistemological underpinnings range from conceiving evidence in terms of “experience” (Scott 1991), “knowledge” (Kelly 2016), “fact” (Lewontin 1991), or “sign”(Hacking 2006). But it can be determined only in relation to “some particular question” (Chandler, Davidson, and Harootunian 1994). In other words, evidence has disciplinary specificity, marshalled through various sets of procedures and protocols.[iii] Harry Collins (1998) coined the term “evidential cultures” to characterize the diverse roles that evidence plays within similar epistemic communities. This concept brings out the varying sensitivities that researchers have towards evidential thresholds, forms of significance, and scales. Despite the doubts one may harbor regarding his distinction between “closed” and “open” evidential cultures, Collins is important in alerting us to the *tacit* dimensions that help to demarcate interesting scientific evidence from mere noise (ibid

: 335). There is, in other words, more to evidence than what can necessarily be captured by formal disciplinary protocols.

If we take a step further back, Simon Schaffer (1992) lends historical weight to the role of sensory forms of evidence through an account of experimental scientific practice in the 1600s. Here the role of the scientist's body was central. Experimenters who used their own bodies, Schaffer argues, "tried to shift the *evidential context* from the body itself to some wider natural philosophical concern" (ibid: 329-330), while their critics attempted to shift the evidential context back to the singularity of the body. What Schaffer thus highlights is a process of "making evidence out of the person of the experimenter" (ibid: 362).

The descriptions to follow in my presentation of ethnographic materials will emphasize the sensorial, tacit nature of evidence within this particular *evidentiary culture*, a culture where the bodies of geologists become one component through which sound is articulated as something legible to evidential protocols. The forthcoming analysis conceptualizes this articulation as a data echo.

The term echo is oftentimes used by historians to describe sound as something that connects us to the past. Mark Smith, a Sound Studies scholar, offers us a way of thinking about echoes: "to varying degrees, it (an echo) is a faded facsimile of an original sound, a reflection of time passed" (2015). These echoes "invite habits of listening that allow us to locate origin (temporally and spatially)" which, according to Smith, shows how historians "whether consciously or unwittingly, think and write about echoes when analyzing sounds of the past" (ibid: 55).

However, as I will show, echoes work rather differently in the present case. In an STS context— particularly within studies of medical technologies—echoes have been conceptualized as forms of vision. Ultrasound technologies, for example, make anatomical features visible as echoes from acoustic signals are picked up through sonic devices. Here, echoes enable a form of “seeing through sound” (Yoxen 1987), making new forms of perception, and new modes of knowing, possible. While Yoxen’s work is situated within earlier STS debates on technological innovation (bringing to light the emergence of ultrasound as a particular technology working to garner representational legitimacy), what the forthcoming analysis will highlight is the role that sound plays—not through sonic technologies and devices but within practices of evidence production and data generation, and, by extension, the forms of knowledge sound enables and decisions it affords. Analogous to Yoxen, however, echoes here enable both *seeing*—understood in the representational sense of rendering the subterranean—and *visioning*—understood as ways of anticipating the future of the volcanic landscape through the lens of a doable problem. As such, sound becomes the means through which the problem of cooling becomes doable in the here and now.

3. Doable Problems

The volcanic cooling problem at Hengill needs to be understood in the context of the adverse effects of the 2008 finance crisis on the Icelandic state and its municipalities. Almost a decade of overzealous borrowing—of which the geothermal power plant was a result—led to Reykjavík Energy being bailed out by the city of Reykjavík on two separate occasions between 2010 and 2014 (Maguire 2020). While the majority within the energy organization were clear that the city could not afford a third bailout, they were equally clear that the citizens of Reykjavik could not live without the services provided by the municipal company. This tension was a palpable concern for the geologists I worked with.

Adequately addressing the problem of volcanic cooling, however, would mean awaiting preliminary results of a simulation modeling system designed to predict the water and steam, and hence heat, flows over the course of many years. This model—operated by the company's lone geophysicist—is extremely detailed and requires vast amounts of data points from various sources over many years (including well drilling and monitoring results, fluid sampling of underground and overground water, production results and other mapping processes). Over the anticipated twenty-five-year life of the project this model was to become the standard bearer. But in terms of the here and now, it was unable to make the cooling problem "doable."

The concept of "doable problems" was coined by Joan Fujimura (1987) to assess the conditions under which scientists decide to construct, pursue, and solve particular problems. Doability is a question of the alignment of various levels of work organization (for example, experiments, labs, and the social). In essence, this involves making experimental work respond to concerns in variously interconnected social worlds. In particular, doability is enhanced in situations where there are adequate resources. Given that resource scarcity and the very real threat of bankruptcy impinged upon the daily life and work of employees at Reykjavík Energy, the only way the problem of cooling could become doable was by creative and ad hoc modes of experimenting. The tracer test became the way to engage this problem in the here and now. Designing and conducting a method that could trace, describe, and model the fracture pathways and flow patterns of the subterranean arteries quickly became the company's highest priority, with geologists working overtime to try and roll out this new method. A sampling team was established to collect fluid samples from over 35 active geothermal wells throughout the Hengill landscape. The analysis of these fluid samples would be the primary data (tracer data) for a new model of the fracture pathways, aiding geologists in assessing why they were losing steam, and hence power, and how this was connected to volcanic cooling more broadly.

The method consisted of injecting 100 kilos of a thermally resistant tracer compound—naphthalene sulfonate—into six different geothermal wells, with each well receiving one of six versions of the compound dissolved in 400 kilos of water. While this initial step lasted a little over two days, sampling the tracer throughout the Hengill's production sites, and the subsequent and on-going analysis of the sampling results, would take the better part of eighteen months. A cluster-sampling regime was initially established in which each production well adjacent to any one of the six-reinjection wells was sampled first. If tracer was detected, the sampling moved on to the next set of adjacent wells, and so on. Over the course of the next year and a half, the entire production area of the Hengill zone was sampled (over 1,500 samples in total) by a rotating team of seven—of which I was one.

Being physically present at the geothermal wells to collect a small sample of fluid in a vial sounds relatively straightforward. In reality, it involved a whole host of difficulties, not least of which was the temperamental, inclement Icelandic weather. At times, the difficult terrain or snow filled pathways demanded journeying on foot as we trekked overground from well to well. Approaching wells to collect water samples necessitated moving cautiously in this landscape. Wellheads rumbled and screeched as explosive fluids accelerated through the extraction pipes, emitting noxious carbon and sulphur gasses. But these geologists took the various forces of the earth seriously—not just as signs of possible danger—but as intricately embedded in how they generated data.

4. Sonic Articulations

The landscape begins to alter as the chief geologist, Bjarni, drives me to the Geothermal Power Plant from the company's head office in Reykjavík. The plant is located a little over thirty kilometers southeast of the city, and about halfway there we enter the purview of the Hengill volcanic system, the tectonic host of the power plant.

Figure 1: Aerial photo of Power Plant, Hengill. Photograph courtesy of Gretar Ivarsson (Reykjavík Energy).

We drive past the main entrance and proceed up the mountainous pathway leading to the geothermal wells. Fifty-seven wellheads, clustered in groups of four on smaller platforms, are scattered throughout this part of the Hengill volcanic zone. Standing at the highest altitude of six hundred meters, a sprawling energy infrastructure lies beneath us. In today's sunlight the pipes carrying the water and steam glisten as they snake their way through the mountain's curvatures.

Being up here on the lava plains is visually striking, but for Bjarni being attentive to the cacophony of screeches and rumblings that pierce our ears is what matters. He comments constantly on the types of sounds the wells make—“did you hear that, it’s screeching, where did that screech come from,” —and frequently invokes battle metaphors to describe what he hears. Screeching is positive, albeit frightening; screeching is what happens when high temperature fluids make their way up the three-kilometer wells. Sometimes the sounds come at regular predictable intervals, but then abruptly change to irregular ones, pulsating, then roaring, and Bjarni pays attention to all of them. This is the sound of phase shifting fluids as they move through the earth, interact with the extraction technologies, and explode up through subsurface-to-surface wells.

As we stand next to the well head and await our opportunity to take a sample, the pipes shake intermittently, yet violently, spasming and wobbling as dense, thick steam billows out. Then the noise stops for a moment, pulsates and screeches again, but a little differently. The wellhead sits like a small silver igloo atop the blackened lava encrusted earth (figure 2), the pipes connected to it are rusted and thick and they pulsate and screech as fluids flow through them. Moving through the sampling pattern, cluster by cluster, the power of the inner earth and the attempts to arrange it feel extraordinarily palpable. As the earth responds to extractive processes, Bjarni and his colleagues heed these responses. What I want to relay in this segment is that listening, or taking account of sound, is one way of doing that. Sound emerges as the differential capacities of heat and pressure respond to the well and piping infrastructure, as excessively hot fluids “fight” their way out of the fractures and up through the wellhead. For wells that go offline and are temporarily disconnected from the system, a silencer is needed; a large bulbously rusted form (see figure 2) that silences the screeching, roaring fluids as they go sonic, breaching the sound barrier to emerge over ground.[iv] “Putting our ears to the ground to reconnect the different strings of the area,” as Bjarni puts it, is, I argue, a lively acoustic method of generating data in this volcanic landscape.

I sample well HE16. Unlike on previous occasions I am now allowed to go to the well alone. I attach the separator to its connection point, protruding out from the rattling and rumbling blackened and rusted pipes, and turn it on.[v] It is not as easy as it looks: HE16 screeches, emitting copious amounts of steam, but no water.

Figure 2: Geologist at geothermal wellhead, Hengill. The wellhead is the igloo like structure to the left of the picture. Following the thick pipe rightwards, there is an additional segment wedged between two pipe sections. The separator is attached here to access fluids. In the background to the right is the silencer. Picture by author.

I become frustrated at not being able to do it right. I open the valve some more, I get more steam, again a little more, but more steam and more bellowing, and at this point the pulsations are frightening. I turn the valve off again, it calms down, I compose myself, and once again turn it on, slightly; it pulsates and screeches as if something really ugly is on the way up. The pipes not only vibrate, they leap with each belch of the earth. My ears are pierced, the steam is dense, full, thick, the smell is all encompassing, penetrating all of my pores, my mouth and my nose simultaneously. The wind is blowing the steam directly into my face, but it’s too hot. I have to try and reposition myself as I saw Bjarni do on many occasions, but I can’t, and need to call for assistance. While collecting a small quantity of water in a vial looks like a relatively straightforward procedure it comes with a learned, embodied way of being around these wells in this landscape, and I am just a novice.

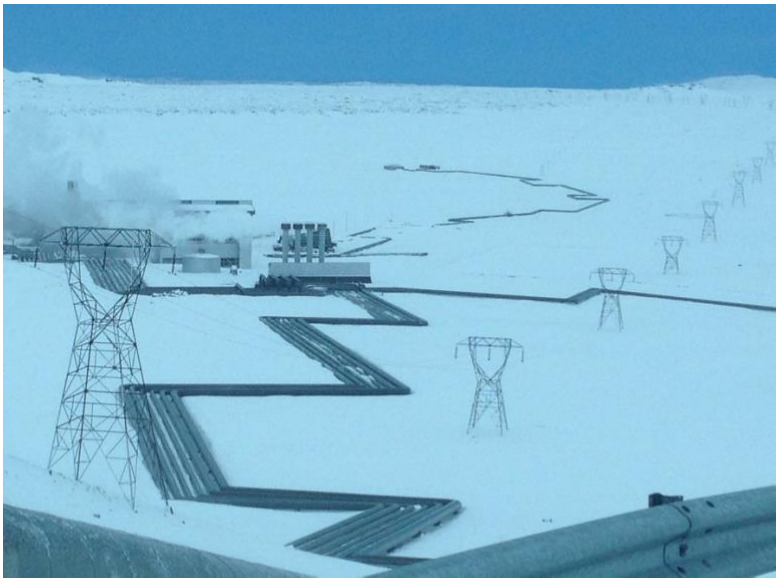

Figure 3: Snow laden landscape at Hengill. Picture by author

On another sampling day a month later, snow is everywhere, and ice has formed at the separator apparatus. I try to stretch my arm and contort my body as if playing Twister, head as far away as is elastically possible. Bjarni saunters over. “What’s the problem?” he asks. “There’s no water,” I bellow. He takes a look, reaches over and turns the valve off. “Wait, listen, then after the noise has passed, turn, gently, that way you’ve more chance of getting water.” Then ever so gently he performs his own instructions, adjusts the valve even as the wind howls and the snow beats against him. Steam pushes out the top half of the separator and trickles of water flow from the bottom end. The noise is now minimum. “There, see, easy, slowly,” he says. “Hmm, like that,” I mumble. Doing this for some time, Bjarni knows how to listen, how to recognize the sounds that come from the wells. He knows the differentiating sensorial forces of the earth, and how to treat pipes to get water, even if they are excessively temperamental. It took me some time to understand what Bjarni meant: why the need to listen to the pulsating responses of the fractures, to wait for the intense sounds to pass? Why does this give more water, and why is this significant? Caring, almost obsessing about the method, Bjarni consistently talked about the only other tracer test conducted in Iceland several years prior, and how it became a "bit of a mess." The mess revolved around how they treated, or did not treat, the relationship between water and sound. Again, and again, Bjarni had to impress upon his team that not all water is the same. For him, sampling is first and foremost a process of trying to identify a specific version of water: tracer water.

The chemical naphthalene sulfonate was considered the optimal tracer for these tests due to its thermal resistivity; it can survive the excessive temperatures of the subterranean. It can also "live" in minute amounts of water that can be transported from well to well by the samplers, so they can unwittingly become an alternative vector, a substitute route that needs to be protected against or in some way excised out of the process.

Migrant water from other wells can easily be present on the gloves, clothes, and instruments of the samplers, and as such can contaminate the sampling process. Bjarni tells me of his stress and sleepless nights thinking about how the test results could be ruined just from one of the guys being careless with their gear. In each wellhead, Bjarni left a pair of gloves and a separator head, to be used at that well only. All of the other accoutrements of the sampling process were stocked up in the jeep for each trip, including boxes of new IKEA glasses to hold the water in, as well as vials and labels used to transfer the water from the wells to the lab.

For Bjarni, being careful about water is crucial to the entire process and taking precautions against migrant water is one step he can make. However, even when the risk of migrant water is minimized, there remains a concern that the sample may still not be the *right* version of sampling water. This is where sound emerges as integral to sampling. Steam, being lighter than water, moves through the system more quickly. When the separator valve is turned on, steam is usually the first to emerge through the pipes. Here is Bjarni again:

> It is very possible that the well will convulse and pulsate, sending up a huge quantity of steam. If that happens then most of the fluid that comes out of the separator would be steam that has condensed into water upon touching the colder exit pipe. Naphthalene sulfonate does not show up in steam, only in water, so it’s possible that a portion of the fluid we get from the separator could be this condensed steam. That would dilute the tracer concentration of our sample, meaning that what shows up in our sample might not represent what is present in the well.[vi]

What this means is that the water we collect in our vials may not be the right type of water, and hence the right type of data. Not getting the right version of water leads to strange and unusable data, as was the case in the previous tracer test in the north of Iceland. Monitoring the response pulses of the well and taking the sample after, or between pulses, was, despite seeming at first insignificant, a centrally important part of tracer sampling. What I want to suggest here is that the geology team have designed an informal acoustic method—a sound-based set of procedures and protocols—that articulates specific sounds as the condition of possibility for what constitutes the right type of water, and hence, meaningful tracer data.

5. Sound as Evidence

While Bjarni and his team took the samples at Hengill, analysis was conducted at ISOR, the Geosurvey Institute of Iceland. Here, each sample was analyzed in terms of the intensity of its tracer content. The results were then modeled and collated into a series of graphs displaying which of the six tracers showed up in which wells, and crucially what time interval it took them to get there. Bjarni and his team referred to the time it takes the tracer to pulsate through the system after it has been reinjected back into the fractures as *response pulses* (figure 4). The amount of tracer that shows up at each production well, its recovery rate, is plotted on a graph relative to the time it takes to get there (figure 5).

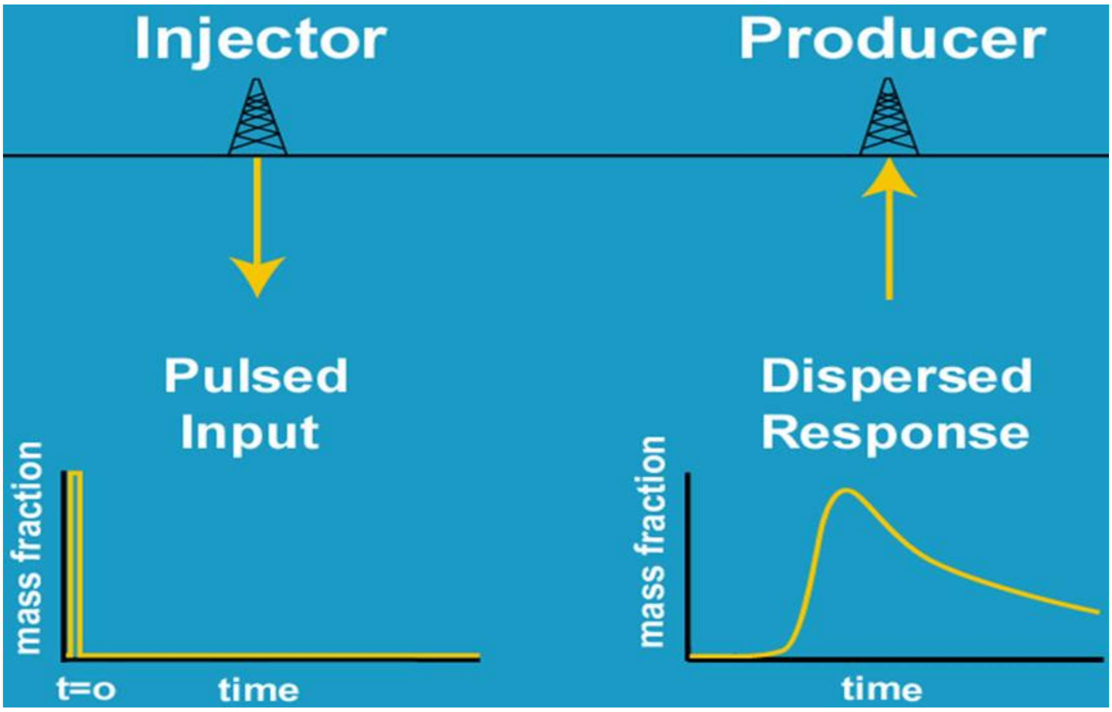

Figure 3: Response Pulses. Image provided by Reykjavík Energy.

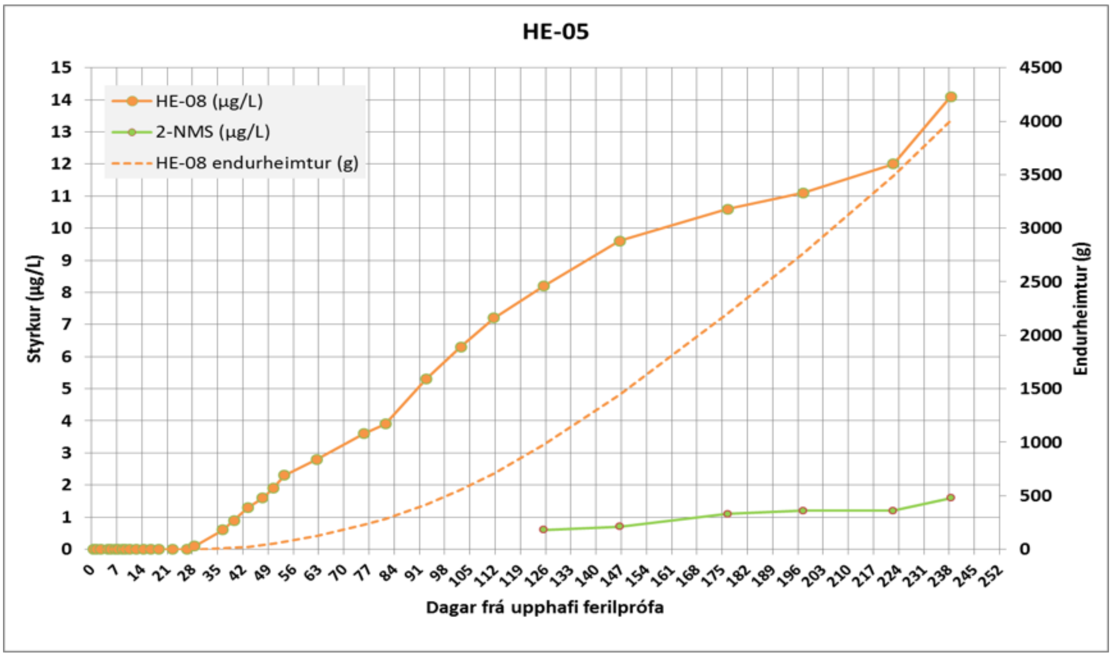

Figure 4: Recovery rate of tracer injected into reinjection well HE-08 showing up at production well HE-05. The X-axis shows number of days while the Y-axis shows concentration of tracer per litre of fluid. The large yellow dots on the thick yellow line indicate samples that register a given concentration of tracer arriving at the well after a given number of days. The right Y-axis shows the cumulative amount of recovered tracer from the well. The dotted line is interpreted as a sharp peak. Each colour on the graph represents a tracer that showed up at production well HE05. Almost the entire recovered tracer comes from reinjection well HEO8 (yellow), with a negligible amount coming from a second tracer (green).

These graphs allow the geologists to develop a temporal profile of each tracer. On the basis of these temporal profiles, the structures that carry the water, that is, the fracture connections and their flow pathways, are simulated. Guðni, the senior geologist at ISOR, explains it like this:

> The timescale tells us about the properties of the geothermal fractures through which the waters are flowing. And by timescale, I mean when you have the peak of the tracer-recovery, how dispersed or broad it is, and how high the concentration is.
>
> Using a simplified model, we simulate the structures that carry the water [the fractures and their flow channels]. Simplified because we can only allow for a one,

> two, or possibly three fracture connections per reinjection well-production well relationship depending on the signal. The simulation provides estimates of the volumes of the connections [flow-paths] as well as their surface areas, because we know, approximately, the lengths of the connections. Then based on some common fracture properties, e.g., expected height and width ratio, we estimate the surface areas of these flow paths.
>
> From the flow path volumes and estimated surface areas we can calculate how the reinjection water is heated up by the rocks along the way to the production wells, and thereby how long it will take the wells to start to cool down over time.

Response pulses are used to generate a temporal profile of the tracer, that is, the pulses of fluid flow are transformed into a temporal mode (days), and these temporal metrics are used to simulate the fracture connections. Here we can see how various versions of what geologists call pulses connect and translate. As I previously described, when sampling water at the wellheads the geologists describe pulses in acoustic terms. Pulses, in this sampling context, are that which occurs between screeching and roaring sonic booms as steam and water ascend and change phase through the apparatus of extraction. These pulses are lulls, the intervals between sounds that signal the right moment to take a sample in order to capture useable water, and hence tracer data. In other words, they are part of an informal acoustic method that articulates the distinction between steam and water upon which tracer data is reliant. In the move from analysis to modeling, these pulses are translated into a temporal form that helps to simulate the fracture pathways of the geothermal reservoir.

Guðni is direct in his assessment of the simulation technique; it is simplified. For example, what he calls strong and clear signals (a high sharp peak on the temporal profile of the tracer, figure 5) gives a one- or two-fracture connection between the reinjection well and the production well where the tracer has shown up.[vii] In this scenario, the signals they are getting allow the connections between areas of the volcanic zone to be simulated in relatively clear terms. On a day when we are having one of our long conversations, I push Bjarni a little on why he uses the simulation model that Guðni and ISOR have developed. Particularly given that Guðni characterizes the model as *simple*. Bjarni explains that the long-term simulation model is not responsive enough to the problem of cooling in the here and now, and that this more simplified approach is what makes the problem doable. Bjarni continues:

> Well, the model is a simplification of reality, I suppose you could call it a more-or-less-reality model. In fact, our reality is the reality of the response pulses between the wells. That helps us simulate the fractures, and we imagine some phenomena that could describe this relation, or these relations. That's what we have to work with.

This phrase, *our reality is the reality of the response pulses between the wells,* is important. Here Bjarni is suggesting that far from trying to represent the subterranean in a holistic sense—an impossible task—they are making a limited version that is good enough for all practical purposes in order to address the particular problem of cooling. In our discussions Bjarni at times characterizes the process as fictional, and at other times as a simplification of reality, but one that, nonetheless, is real, and necessary given the broader financial conditions of the company, and city.

Tracer data help these geologists to estimate where the water is flowing to, and in what time frame it is showing up, which in turn allows them to develop production strategies that best optimize reinjection flows. At the same time, it also allows them to estimate what, if any, cooling effects pumping vast quantities of water back into the rock matrix is having. Above, Guðni explains that when they have simulated the fracture connections, they estimate the surface area of their flow paths in order to calculate how reinjection water is heated up by the rocks along the way to the production wells, and thereby how long it will take the wells to start to cool down over time. Bjarni parses this in more analytic terms, saying that simulating the fractures between the wells is a way of imagining fractures as a type of phenomena that can help them describe other sets of relations. Generating a "doable" version of the subterranean through tracing is also, then, a descriptive technique that allows geologists to describe other relations between rock, water and heat, relations constitutive of potential volcanic cooling.

Understanding heat relations between flowing fluids and rock is key. In essence, how, over time, reinjected water extracts heat from the rocks as it flows through the subterranean arteries of the geothermal reservoir. What is crucial is the speed at which reinjected water travels from one area to another. As rock is a poor conductor of heat, it needs ample time to regenerate the heat transferred to the water flowing within the rock matrix. The faster water travels, the more heat it picks up from the rocks. There is a particular architecture to this: as water flow speeds up it moves through phases, from uniform (laminar), to wavy (convective), to turbulent. It is this latter turbulent phase that extracts heat most aggressively from the rock. The inverse is the case for slower moving water.[viii]

What the tracer data show is that one of the priority production areas, the mountain Skarðsmýrarfjall, which lies next to the central volcano, is not recovering from extraction-reinjection practices. In fact, the preliminary results of Bjarni and Guðni's work show cooling that will not only significantly affect production over the course of the next twenty-five years—and is already doing so—but will also inhibit the mountain from recovering over the next one thousand years. The tracer acts as a proxy for flowing water because it has, in a sense, different relations with the world. By different relations I mean that as a thermally resistant chemical it does not interact with the rocks in the same way as flowing water, and as such travels more quickly than water through the fracture matrix. In this way its pulse is a form of future agent, simulating not how water acts now, but how water will act several thousand years into the future. Because the chemical signal of the tracer shows up earlier than the thermal signal of the water, analyzing the time of the tracer allows geologists to predict the time of the cooling. Bjarni and his team work with a very simplified rule of thumb: if the peak of the temporal pulse profile is, for example, one month, then the cooling will follow approximately 1,000 months later.

Tracer data work analogically by creating a specific type of relation with the future, a relation of proportion (1:1000).[ix] Telling the time of the tracer today allows geologists to estimate the time of the future; the time of cooling. Making these predictions is, as we have seen, facilitated through a series of translations between the volcanic landscape and the lab. And it is paying attention to the various sounds, which are articulated through the apparatus of extraction, that index this relationship in the first instance. Tracer data are the evidence that these geologists now mobilize to argue for a slowing down of extraction practices, which, in their estimation of heat relations, would give the area more time to recover its heat loss. As the extractive pulses of the landscape are accelerating, telling the time of the future is one way of creating attention around, and directing action to, this problem of cooling.

6. Data Echoes

As shown above, taking fluid samples from geothermal wells after, or between, sound pulses, was centrally important to the tracing project. In this sampling, sound emerged as a crucial *articulation*: the geologists' informal acoustic method articulated sound across an assemblage of actors (subterranean processes, the apparatus of extraction, and the geologists). But as we have also seen, this articulation is not *simply* sonic. It is multi-sensorial; shaped by various senses that facilitate the ability to perceive, and isolate, sound pulses as they belch, roar and pulsate through the technologies of extraction. Crucially, sight and smell render these soundscapes meaningful to the establishment of evidence within evidence, and hence, to data production. To recapitulate: the tracer present in the sample can only be accurately gauged if it can be determined that steam is not present as condensed water. This requires listening. Waiting for the roar through the apparatus of extraction to subside before taking a water sample is thus the way to ensure that the right type of water is sampled. Hence, sound is what allows the geologists to differentiate evidence from noise. As evidence, water becomes important data. As noise, condensed steam is considered a contaminant. These data are subsequently used as evidence of volcanic cooling.

What is elicited from these descriptions, then, is the evidential culture of the geologists, one that operates through a *double* articulation. Within what might be called the primary evidence of volcanic cooling (tracer water as data) resides something else that must be sonically detected in order to establish that this primary evidence is, in fact, evidence. This primary evidence—subsequently discussed in geological reports—is first rendered as evidence by geologists using their own bodies as sonic detectors within these volcanic soundscapes. Tacitly operating as evidence within the evidence on the outside of formal disciplinary protocols can be termed *data echoes.*

As discussed in an earlier section of the paper, the term echo is oftentimes used by historians to describe sound as something that connects us to the past. However, in contrast with the conventional orientation of echoes to the past, data echoes as I have described them, have a strong future-oriented dimension. As sonic evidence within the primary evidence of volcanic cooling, sound lingers as a *data echo*: a sonic form that facilities this double articulation. As evidence within evidence, these sounds are not materialized in tracer data as such, in the way that, for example, sound is materialized as recordings within other evidential protocols (such as in law). As sonic forms, these echoes instead reverberate more than they translate, becoming the acoustic basis upon which fractures can be simulated, heat relations modeled, and cooling predictions rendered. So, while the habits of listening for these geologists are embedded within the tracer test, I am arguing that such habits, as informal method, help them to describe, not temporal origins, but futures. As data echoes through the various moments of data capture, analysis, and model building, sound's temporal form helps to predict the timeframe of volcanic cooling, both as it affects the immediate production scenarios of Reykjavik Energy, and the long durée of volcanic time.

7. Conclusion

In her ethnography of making environmental data in the Brazilian Amazon, Antonia Walford (2017) highlighted that excessive relationality was often a central problem. Her point was not simply that data are actually composed of heterogeneous relations—although this is important—but that most of what appears to be data never ends up as such because it remains *too relational*. Figuring out how to sort and select seeming and "real" data is a major form of invisible, scientific work. This article corroborates that insight in the very different context of Iceland's volcanic landscapes. Here, geologists use sonic articulations to detect data echoes that *provide evidence that they are dealing with evidence*.

Walford emphasizes a shift from viewing the results of scientific work as the production of facts constituted by a myriad of relations, to seeing the results of scientific work as the production of the relation that makes the distinction between facts and relations possible (ibid: 76). As I have shown, sound helps Icelandic geologists to constitute such relations: without informal acoustic methods the relevant distinctions could not be made, and their problems would not be doable.

In this way, sound enables an articulation between evidential protocols. As echo it works as an outside (Riles 2001), which, while remaining external to official protocols of knowledge production, nevertheless helps to constitute distinctions that are meaningful to the production of those categories. In that sense sound remains *within* and *without*: within the suite of methods that these geologists deploy, yet without their official protocol descriptions.

As evidence within the evidence of volcanic cooling, sound, the paper has argued, lingers as a data echo; a sonic form that echoes between forms of evidence, and through various other stages of data making enabling the modeling and visioning of alternate energy scenarios. Such data echo into the future as their temporal form helps to anticipate the future of, and generate options about, the ongoing role of renewable energy production in decarbonized futures.

Acknowledgements

I would like to thank both ST&HV reviewers for their careful and generous engagement with earlier versions of this article, which was invaluable to its development.

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[i] Extracted steam and water are used to generate hot water for heating, and electricity for aluminum. After mining the heat from these fluids, the colder remnant water is re-injected back into the subterranean. It is specifically this process that geologists suspect is cooling down the area. Tracing this water is the primary ambition of the tracer test.

[ii] Helmreich asks, who or what is doing the listening in gravitational-wave astronomy? The discipline itself (in opening its ears to the cosmos), the LIGO experimental system (the detection system), a computer algorithm, and the scientists themselves, he suggests.

[iii] STS has examined questions of evidence in numerous settings. In particular, the rise of 'evidence-based medicine' (Timmermans and Berg 2010) and its associated 'evidence-based guidelines' and 'evidence-based policy' (van Loon and Bal 2014, Davies and Nutley 2000) have garnered significant attention. Michael Lynch has talked about the role of scientific evidence in legal terms, and specifically the special epistemological status that DNA has generated in recent years (2013).

[iv] Once drilled and activated geothermal wells cannot be turned off in any strict sense. All wells are connected to the piping infrastructure, operating at 7 bars of pressure. When a well needs to be cleaned or undergo maintenance it goes offline, that is, it is temporarily disconnected from the system but continues to produce fluids. These fluids are routed to what is called a Silencer, a large container like object that dampens the sonic sounds. Even with the Silencer in operation, the sounds are incredibly loud and penetrating.

[v] In order to take a sample of fluid from the wellhead, a separator needs to be connected to the larger piping infrastructure. It is a small one-meter implement that fits onto the foremost section of pipe. As a mobile add-on it allows geologists to sample fluids at the wellhead without disturbing the flow of fluids through the pipes on their way to the plant.

[vi] Bjarni also instigated a periodic control check on the sampling process. Taking a second sample at particular points during the day, the chlorine content of the sample was analyzed as a way to check the ratio of water to condensed water (steam). If the sample has, for example, 100 ppm of chlorine and the well has a given chlorine content of 200 ppm then the inference is that the sample, containing half the usual chlorine, is 50% condensed water. As neither chlorine nor the tracer molecule Naphthalene sulfonate show up in condensed water, chlorine can function as a proxy for the tracer. In this instance the tracer recovery rate in the fluid of

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that sample is adjusted by this quantity, that is, it is doubled. This can then be compared against the tracer content of the original sample and an average variation can be established as a correction mechanism.

[vii] This would be where there is a strong percentage recovery of tracer over a short period of time, that is, a sharp, less dispersed peak.

[viii] Several things affect the speed at which water travels through the rock matrix from one area to another. The quantity and pressure of the water being reinjected back into the fractures (this is dependent on the rate of extraction), the temperature of that water, as well as the quantity and structure of the fractures and their flow pathways between different areas.

[ix] One way to think of analogies is in terms of proportion, that is, a relation, reference or order of one thing or principle to another. Take the number couplets 2:4 and 8:16. We know that 2 is not 8 or that 4 is not 16, but we do learn something about a relationship or structure that inheres in them which is applicable to other sets of similar number couplets. Another example would be the way a ship produces on the water an effect similar to that which a plough produces on a field. Analogy renders intelligible relations between things, which might otherwise not be obvious. For Aristotle this was to 'perceive the similarities of dissimilars' (Kelly: 1996), which for Wittgenstein was a question of words existing within language games that share a 'family resemblance' (1973).