

Response to reviewer 1

General Comments This is a fascinating study which brings together seismologists, artists and researchers from the schools of English, Earth Science and Art History at the University of Bristol. This unique variety of expertise allows for the analysis of seismic signals and their perception by people in ways that have not been considered before, bringing a refreshing perspective to seismic studies from a new angle.

Specific comments: In section 2.5 in the last couple of sentences there is some confusion about the relationship between earthquake magnitude, signal amplitude and event energy release. As written it implies that the relationship between magnitude and amplitude (x10 for one unit) is similar to that for energy but then goes on to say that this is a x32 per unit magnitude relationship. This could be clarified to differentiate better between the two relationships. - - [the phrasing on these sentences was changed to make the meaning clearer to the readers.](#)

In section 2.6 (line 351-352) it states that a Modified Mercalli intensity value of V -VI corresponds to a magnitude 5 on the richter scale. In order to avoid confusion between intensity and magnitude concepts it would be better to modify this statement along the lines of " ... corresponds to the shaking experienced close to the epicentre of an earthquake with a magnitude of 5 ... " [corrected](#)

In section 2.6 (line384) it states that the mechanism for bells ringing remains unclear. I would have liked to see a discussion at this point about the possible effects of resonance between the seismic wave frequency and the natural oscillation frequency of either the clapper/bell system or the whole belltower structure : [We have worked on making this discussion more robust and tried to include tie-ins to the fundamental frequency of buildings and possible resonance effects.](#)

In section 2.7 during the discussion of collaborations with artists I was disappointed to not see a more detailed discussion of this aspect of the work. As the artistic collaborations involved visual (dance) and auditory (soundscape) pieces I understand that it is difficult to convey their content in a written article. However as this collaboration is one of the unique and innovative aspects of this work I had hoped to see some more reflection on this work, maybe in the form of quotes from the performers or audience describing their emotional responses to the work (or even in the form of mood boards or wordclouds): [Thanks for](#)

pointing this out; we have gathered some thoughts from attendees and participants of these artistic workshops and have incorporated them into the revised manuscript.

In section 4 (line584) the raspberryshake citizen sensors are described as using MEMS sensors. While
30 raspberryshake systems are available as MEMS based systems their sensitivity is so low that they only work
as strong motion sensors in zones of high seismicity. In the UK the raspberryshake data analysed in this
paper all comes from the geophone based raspberryshake sensors which use a conventional geophone
system (with a natural low frequency limit of 4.5hz which is electronically modified to give it a frequency
response of 1Hz-40Hz) – We have changed the text to reflect this variation in UK raspberry shakes.

35 Technical corrections typo line 282 "understand" should read "underside" typo line 543 - corrected

"in and impermeable" should read "in an impermeable" - corrected

Response to Reviewer 2

1 General comments

Reading this work led me to two papers that I find very interesting, and I would like to share it with the
40 authors:

- a) Urban Seismology: On the origin of earth vibrations within a city, November 2017, Scientific Reports 7(1), DOI: 10.1038/s41598-017-15499-y

I read the Urban Seismology paper and attempted some of their analysis for 2 separate weeks of data - a week in May and one
in December. I do not report this analysis in the paper because the trend that we observed was somewhat different from what
45 they reported where weekends are quieter than weekdays. As demonstrated in figures 4 to 6, weekend activity near the
university appears to be higher than weekday activity. The data also showed no significant activity around New Years that
could have been interpreted as fireworks. I have added a line in the text acknowledging the departure in these observation
between our study and Diaz

- b) Seismometers Within Cities: A Tool to Connect Earth Sciences and Society, Front. Earth Sci., 05 February
50 2020 | <https://doi.org/10.3389/feart.2020.00009> (Jordi Diaz , Martin Schimmel, Mario Ruiz and Ramon Carbonell)

When I first read the paper, I thought (by the abstract) that it would be a paper on urban seismology, something in the line that Díaz et al (2020) had done in their work about urban seismic noise in Barcelona. If this was the case, I would have missed a discussion on the physics that underlies the bell-ringing due to ground shaking, and a more refined exploration of different urban sources that were identified in the seismogram.

But in my opinion, the main contribution of this research is the interdisciplinary aspects of urban monitoring, which is indeed very interesting, but it is not what the abstract emphasizes. I suggest the authors to emphasize that this paper is interdisciplinary research that will investigate human connection to seismic vibrations under the point of view of music, poems, theatre and geophysics. And I agree with Paul Denton's comment that more reflection on the collaboration with artists would be very welcome. *We have edited the abstract to make the multidisciplinary collaboration clearer.*

2 Specific comments

L190 It would be nice to draw an arrow or a square showing the events of the bell- ringing in Figure 4. Specially because this paper might be read by non-geophysicists. *I think the bell signals are very clear in the 10 pm spectrogram (especially in the frequency bands that I mention) and there would be too many arrows on the Charter Day chime which would make the figure too busy. To facilitate easier identification of the chimes, I have added arrows at the start and end of the chiming sequence.*

L255 Missed reference for the Indonesian tsunami, that is present in the references list. *I'm not sure what you mean – Goda 2019 is cited both in the text and listed in the references*

L245 I suggest to specify the station name -*added*

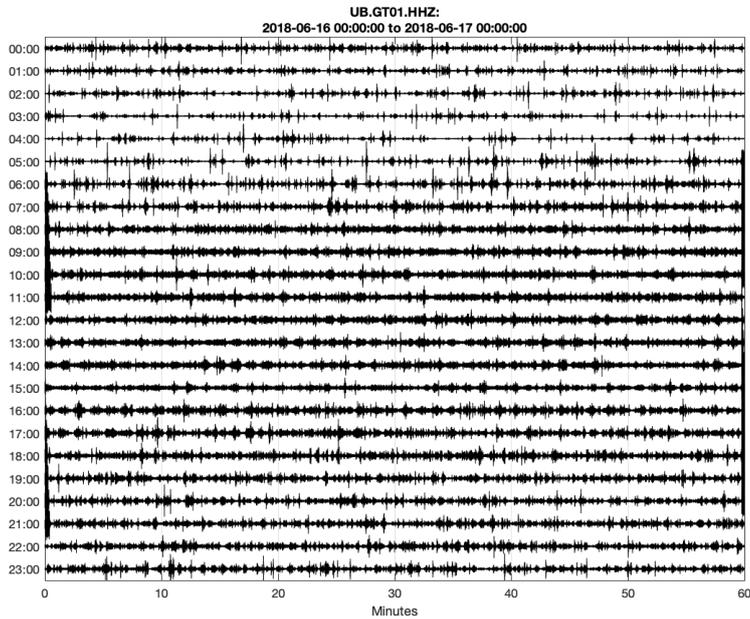
L255 Where is Market Rasen? *Added the county plus latitude/longitude for Market Rasen in the revised manuscript.*

L313 Where the authors put: "A look at the data. . ." I suggest to indicate a Figure – *Added a reference to figure 11.*

Figure 5 The plot shows the whole band (0.01 to 50Hz) or you used a filter? I would like to suggest the plot of a filtered version of this Figure, for the band 15Hz to 25 Hz, in which the authors observed the Great George peals (or I would give a try to 20-30Hz band, by Figure 6). Maybe the other events that are visible in Figure 5 would vanish, or appear in some other frequency range? There are some peaks that seems to be regular, would they be subway noise, or something like that? - *There does not appear to be a significant*

difference in the helicorder record filtered between 15 - 30 Hz band from the unfiltered data when looking at a full day (see the figure below which shows the same data as in figure 5b now filtered between 15-30 Hz). I really do not observe any regularity in the pattern like Diaz saw in his data set. This is probably because the closest train station is ~ 1 km away from the site and there are no underground systems in Bristol. Further, while the tower sits between two traffic lights (less than 100 m away from either light), I have not observed any true regularity to the length of the traffic lights and hence in the data. The Bristol City Council uses an automated traffic light system that manages the traffic lights in real time based on the traffic approaching junctions and crossings; as such, I believe the length of the traffic lights is variable throughout the day as traffic volume changes.

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3 Technical corrections

Please note that I am not an English native speaker, and my English is brazilian biased. I will point out some typos that I found, and give some suggestions that I kindly ask the authors to evaluate if they are

- pertinent. I put in red what I think should be erased, and in blue new words or letters that should be
- 95 included. We have incorporated the majority of the changes that you have suggested here.
- L10,L195 I think “bell-ringing” has a hyphen corrected
- L14 nearly continuous, or near-continuous instead of near continuous - corrected
- L19 earth-shaking events (add a hyphen) corrected
- L20 Replace “in order to” with only “to” corrected
- 100 L53 the authors had already used the expression “daily basis”, so I suggest changing to “ground shaking
daily” corrected
- L66 remove comma “in a different and more connected way” corrected
- L73 “others in minutes and in millions of years” Amended this sentence slightly.
- L77 “partly from professional activities but also from personal trajectories” corrected
- 105 L196,L334 I think “zoomed-in” has a hyphen corrected
- L196 remove “clearly” corrected
- L200 Change “there are three noteworthy features that are” to “three noteworthy features are” corrected
- L220,L249 “high-frequency” has a hyphen corrected
- L250 “often requires” corrected
- 110 L258 “The P-wave and S-wave arrivals are clearly visible at station LMK” While we are aware that stating
that something is “clear” to see is a bit of a sticky subject, we use the term clearly to signify how much
stronger the signal appears on the nearby station as opposed to ours. We do go through the exercise of
explaining what P and S waves are so I think that the non-geophysicist would be aware of what to look for
and not have a hard time finding the signal “clear” to see
- 115 L286 “there are a number of many current research endeavours to study these more exotic signals.”
corrected
- L295 I think “Modern-day” seismologists has a hyphen corrected
- L302 “signal is clearly visible above the regular activity near the tower (see Fig. 10)” – removed
- L303 “the Greece event occurred closer to Bristol and was, therefore, more clearly visible.” (add commas)
- 120 corrected
- L321 “amplified in tall buildings particularly, when they are impacted by low” (remove comma) corrected
- L358 “This calculation shows that there is clearly a large amount of energy” corrected

- L403 “presents these sounds via three **subwoofers** and...” **corrected**
- L421 “media player will outlast the 21st-century” **corrected**
- 125 L535 “geothermal activity, or other catastrophes” (plural) – **corrected**
- L543 formations that contain gas trapped in **and impermeable**” **corrected**
- L584 “use a MEMS (**micro-electro-mechanical-systems**)” **corrected**
- L586 “and there are currently more **that than** 50 Raspberry Shake” **corrected**
- L617 “where the waves travel around the inside of the Earth **are is**” **corrected**
- 130 L618 “**Reciprocally In a reciprocal way**, such realizations” **corrected**
- L625 “by expanding the reach of our hearing and extending our **own** auditory map” **corrected**
- L643 “vibrations travelling **through**” - **corrected**
- L652 “**Aknowledgements**” -**corrected**
- L669 “The numbers in the upper right corner of each trace indicates” - **corrected**
- 135 L683 **Spectograms** - **corrected**
- L690 “between signal duration on **bother**” **corrected**
- L379 (Blakeborough, 2001) check citing format **corrected**
- L436 (see also Nicols(2014)) check citing format

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Good Vibrations: Living with the Motions of our Unsettled Planet

140 Tamsin Badcoe¹, Ophelia Ann George², Lucy Donkin³, Shirley Pegna⁴, John Michael Kendall^{2,5}

¹Department of English, University of Bristol, Bristol, UK

²School of Earth Sciences, University of Bristol, Bristol, UK

³Department of History of Art, University of Bristol, Bristol, UK

⁴Sound Artist, Bristol, UK

145 ⁵Now at Department of Earth Sciences, University of Oxford, Oxford, UK

Correspondence to: ophelia.george@bristol.ac.uk

150 **Abstract.** By its very nature Earth is unsettled and in continual motion. Earthquakes and volcanoes are an expression of the convective motions of the planet and our existence on Earth is a consequence of this tectonic activity. Yet, as humans, we often struggle to understand our role in relation to such unpredictable natural phenomena and use different methods to attempt to find order in nature’s chaos. In dwelling on the surface of our “unsettled planet”, we adapt and live with a range of ground vibrations, both natural and anthropogenic in origin. Our project, funded by the University of Bristol’s Brigstow Institute, seeks to explore how we perceive and understand the shaky ground we live on, using an interdisciplinary approach that brings

together the Earth Sciences, the History of Art and Literature, and Performance Art. Inspired by historical commentary in the aftermath of large earthquakes, which frequently notes the unscheduled ringing of church bells excited by the shaking around them, we reflect on how these purported unscheduled bell-ringing events were caused not only by near earthquakes but also by distant incidents. To investigate this phenomenon, we installed a state-of-the-art broadband seismometer in the Wills Memorial Building tower to record how Great George (the tower bell) responds to the restless world around him. The installed seismometer has been recording activity around and within the tower on a near-continuous basis between late March 2018 and January 2019. Here, we present the signals recorded by the seismometer as Great George overlooks the hustle and bustle of the city around him and investigate how connected we are to our "unsettled planet", even from our tectonically quiet setting in Bristol. We find that the seismometer not only shows the hem and haw of activity in and around Bristol, but also registers earthquakes from as nearby as Lincolnshire, UK, or as far away as Fiji, halfway around the world. In order to contextualise our findings, our project also considers what determines how people have responded to earth-shaking events, drawing on both historical and recent examples, and looks to contemporary art practice to consider how an awareness of our "unsettled planet" can be communicated in new ways. The project has led to a number of art installations and performances, and feedback from artists and audiences shows how making art can be used both to investigate our connections with the Earth and to articulate, and even accept, the uncertainties inherent in encountering unstable ground.

1 Introduction – the Unsettled Planet Project

People live with the ground shaking on a daily basis but when and why we become aware of this is contextual. To varying degrees our capacity to dwell on the surface of the Earth is shaped by a learned tolerance of vibrations – sometimes benevolent and commonplace, at other times potentially calamitous – beneath and through our spaces of habitation. From the measurable footfall of humans walking along a pedestrian street in Bristol and the locomotion of individual elephants in Kenya, to the co-ordinated motion of a stadium crowd and the combined impact of traffic noise, our world reverberates with the forces generated by human, animal and vehicular activity. The resulting vibrations go largely unnoticed as the ground motion that they produce is relatively small and fades into the hustle of everyday life. More attention grabbing, of course, are the vibrations produced by phenomena such as earthquakes.

Whether large or small, these vibrations provide vital information not only about the settings in which we live but also about the natural world around us and how we react to it. Just as footsteps are easier to discern when made on a creaky floor than they are on solid ground, so too does the setting in which Earth-shaking occurs affect our perception of events. The 1985 magnitude 8 earthquake, 350 km away from Mexico City, for example, caused significant damage and loss of life. The extent of the damage was due to the nature of the ground beneath the city (Seed et al., 1988). Centuries earlier, as Nichols (2014) observes of the devastating 1755 Lisbon earthquake, "the historic Baixia area on the north side of the Tagus, the seat of government, with narrow streets and timber-built houses, rested on water-saturated alluvial sediment" that "liquefied during

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the earthquake and lost its bearing strength during the shockwaves. Down the coast, Tavira, sitting on limestone met with few casualties". Furthermore, human-induced earthquakes in Lancashire – due to hydraulic fracture stimulation (fracking) – register differently in the public consciousness (Williams et al., 2017) than much larger natural earthquakes in more seismically active regions such as Japan. An earthquake can thus be a disaster for one person, slightly worrying for another and barely perceptible for many more. The factors shaping individual responses might be simply determined by proximity to an earthquake but are more often influenced by other considerations including the underlying geology, local culture, collective memory, a familiarity with the associated phenomena, and the inequalities of disaster management. Living on an unsettled planet such as ours is tolerable for most of the time, but at others can be catastrophic.

This paper offers reflections on an interdisciplinary project that explored the relationship between scales of Earth-shaking and thresholds of habituation. A response to the theme of "living well with uncertainty" proposed by the University of Bristol's Brighstow Institute, the project brought together a sound artist and researchers from the Arts, Humanities and Earth Sciences at the University. We found ourselves particularly interested in how people react to first-hand experiences with the fact that the ground is not stable or firm. At one extreme, this involved thinking about living in earthquake prone regions, and at the other, considering how someone from the countryside might find it unsettling to live in a city with heavy traffic vibrations. Indeed, as we discovered, thinking about how people live with the ground shaking daily does not just apply to distant places, rich in seismic activity, poised on fault line, but can also be used to consider our own located positions, which for the purposes of the project, took in the steep incline of Park Street and the Wills Memorial Building in Bristol: surely, the epitome of solid ground. Even familiar territory, we found, is constantly on the move, impacted both by our own bodies and by seismic events across the world. In the School of Earth Sciences, for example, our conversations took place against a background of heavy traffic vibration caused by buses passing by immediately outside the windows of the Wills Memorial Building: vibrations ultimately equivalent to those that might reach Bristol from a distant earthquake. In combining approaches drawn from geophysics, the humanities, and the arts, then, we connected different categories of knowledge-making in order to grasp what is there or what could be there, not only under, but also passing through, the ground beneath our feet, and made links between what we know and what we imagine. The project focused on the current discourses surrounding controversial issues such as fracking but looked at how past perceptions of seismic and volcanic hazards have evolved over time. We specifically aimed to probe the effects of seismic vibrations from regions of the Earth that are both near to and far from our relative haven in Bristol and to reflect on how those events are perceived by those around us. Our group aim was to engage with the sounding phenomena around us, thus enabling us to perceive the world in a different, and more connected way.

Within our interdisciplinary team of co-authors, we found marked differences in our ways of working. It was easy to recognise this methodological range, but its implications were harder to fathom. We could use labels that corresponded to the badges of our professions – Earth Sciences, literary and historical studies, artistic practice – but the project asked us to think about our default settings and manner of approaching things. Some of us are more attentive to sounds, some of us to words, some to

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images, some to things, and some to numbers. Some of us think mainly in decades and centuries, others in minutes or even in millions of years. We did not strain to find common ground; after all, we have a collective interest in the ground beneath our feet. It was always easy to talk, but this has involved a particular kind of conversion, which one participant described as "specialists speaking colloquially". Of course, we are also more than our disciplines. What we each brought to the discussion was dependent on the parts of the Earth's surface with which we are familiar: a frame of reference which came partly from professional activities but also personal trajectories. Anecdotes, questions, lines from a poem, an image, identities; all of these provided points of connection, but we ultimately found collective stimulus in a bell.

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245 1.1 Great George and the Wills Memorial Building

Great George (the bell in the tower of the Wills Memorial Building) became something of an emblem for us, in that it offered a fusion of vibrant matter and symbolic resonance (Bennett, 2010). As a material object specifically designed and fabricated to resound in a particular way, the bell participates physically in the marking of time but also acts as a reminder of how bells have historically sounded in times of celebration, admonition, and mourning. By using the bell as an instrument for registering vibration, whether that caused by the passage of buses on Park Street or that generated by seismic activity a thousand kilometres away, we reflected on technologies of recording, both those designed with a specific purpose in mind and those repurposed and used inventively and creatively. In its capacity to register vibrations, then, the bell's purpose as percussive instrument was revised, using the addition of a seismometer (Fig. 1), to become an instrument of measurement: a transformation that also asked us to think about how solid bodies, including our own, register the unpredictable motion of our unsettled planet. Bells have often been anthropomorphised, given human names and marked with inscriptions couched in the first person. If the place of Great George in the project lay partly in the rich potential of using a bell as an object to think with, its importance for us also owed something to the fact that it was physically present above us in the building in which we generally met, and audible wherever we were in the city. Great George is an object that can be visited, touched, and even swung: an object that was already multi-vocal and expansive, in terms of both its E-flat tone – audible up to 20 kilometres away – and its twitter feed, with a potentially global reach. The material qualities of the historic bell, cast in 1924, became particularly compelling when put into dialogue with modern scientific equipment, which was as exotic and mysterious to some of us as it was familiar to others.

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1.2 Thumbing through the Special Collections

The project also involved encounters with objects that were more familiar to those of us working in the arts and humanities. A workshop in the Special Collections of the University Library allowed us to look together at printed material on earthquakes ranging from the sixteenth to the nineteenth century, drawn mainly from the Eyles Collection (Eyles and Eyles, 1679 - 1983). Here, the objects of our attention were sometimes fragile books resting on foam cradles, pages held down with snake weights – works with evocative paragraph-long titles such as "A true and exact relation of the most dreadful earthquake which happened in the City of Naples and several parts of that Kingdom, June the 5th, 1688: whereby about forty cities and villages were either

275 wholly ruin'd or extremly damnified; eight thousand persons destroy'd and about eight hundred wounded; of which four
hundred were digg'd out of the ruins, and many others miraculously preserved, translated from the Italian copy printed at
Naples, by an eye-witness of those miserable ruins" (J.P., 1688). We scrutinized striking images such as Athanasius Kircher's
cross-sections of the Earth (Kircher, 2015), previously met as disembodied images on the web (a very different experience
from turning the pages of *Mundus Subterraneus*, [first printed in Latin in 1665](#), in its published book form). Voices from the
280 past included descriptions of the sensations and emotions engendered by moving ground, but also attempts to explain seismic
activity, whether in terms of human wrongdoing and divine punishment or in terms of natural process. For the scientists
amongst us, this brought home not only the differences in how science was conducted in previous centuries but also the
resonances still perceptible with ideas held today. For those of us accustomed to the objects and setting of a rare books
collection, it was appreciable how the process of collaborative looking and reading differed from the sustained attention and
285 focused questions of personal research. As we all circulated amongst the works, pointing out aspects and reading out passages
– some of us more drawn to human testimony, others to scientific thinking – we provided contexts and explanations drawn
from our own disciplinary frameworks.

1.3 Public colloquium

A one-day public colloquium allowed us to share some of our developing ideas with a wider audience and to benefit from the
290 expertise and insights of others. Part of the day adopted a traditional format of short papers. Three invited speakers discussed
projects that independently involved dialogue between disciplines and audiences. Stephen Vaughan, a photographer from the
University of Bath Spa, spoke about his work on the impact of earthquakes in Japan and the United States. His focus on
earthquake-induced tsunamis encouraged us to include water more fully in our thinking. By exploring how individual seismic
events are discernible in the geological and dendrochronological record on both shores of the Pacific, he also gave us another
295 way to think about distance and how seismic activity connects places. Paula Koelemeijer, an [Earth scientist](#) then at the
University of Oxford, reported on research conducted with Beth Mortimer (Mortimer et al., 2018), a biological scientist at the
University of Bristol, bringing animals into the conversation. Not only was this research team able to track the movement of
the elephants, differentiate between them and determine the kind of ground they were traversing, but they hypothesized that
the elephants themselves were possibly able to communicate in this way, picking up on different frequencies produced by the
300 tread of fellow elephants across distances of 10s to 100s of kilometres. Paul Denton from the British Geological Survey spoke
about crowd generated earthquakes. Since the bulk of conversations about human-induced seismicity surrounds activities such
as fracking, it was surprising for many to learn that amassed human footfall during outdoor rock concerts or football games
could result in ground vibrations equivalent to those induced by a magnitude 2-3 earthquake a few kilometres away. Low cost
seismometers, built from Lego, for example, and installed in schools can pick up such vibrations as well as other earthquakes,
305 extending the kinds of possible audience invited to attend to the movement of the unsettled planet.

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310 Within the lecture theatre, charismatic objects from science and artistic practice helped to make ideas concrete. Speakers passed
around 3D printed models of the Earth and a fired-clay disc inscribed with a sound wave in the manner of an LP. At the edge
of the stage, a different kind of speaker – a huge amplifier – formed an intriguing presence, already reminding us of the sonic
quality of seismic activity before allowing everyone to hear and feel the movement recorded by Great George the bell.
Participants also gained a new awareness of the unsettled ground beneath the building by inhabiting other spaces, heading up
the tower to meet Great George himself and look out over his soundscape, and sitting in a van at the base of the tower to listen
to the amplified steps of passers-by (Fig. 2).

315 These activities were carried out concurrent with our seismic instrumentation of the bell tower. In the following sections, we
describe the setup of our experiment as well as the data that we gathered from the instrument between March 2018 and January
2019. We describe the data gathered in the context of how our bell tower is positioned not only within the interactions of our
city but also in a larger global picture.

320 **2 Data Summary – monitoring the world from a bell tower**

To quantify the contemporary vibrations of our unsettled planet, we used two methods to collect seismic data. The bulk of
these data were collected in and around the Wills Memorial Building (WMB). The WMB tower is a Neo Gothic reinforced
concrete structure which stands 65.5 meters above the street level and is 16 square meters at its base. Topping the tower is an
octagonal lantern which houses Great George. Great George is a large E-flat bell that measures 2 meters tall by 2.5 meters
325 wide and weighs approximately 9.5 tonnes (Ringing For England, 2019; Towerbells.org, 2019), making it one of the largest
bells in the UK. Great George rings hourly by the action of an external clapper except on special occasions such as the
University Charter Day when it is rung in the traditional way by experienced bell ringers using an internal clapper.

330 The first of the two data collection methods utilized a 10 Hz vertical geophone which was embedded in the shallow subsurface
outside the WMB (Fig. 2). A geophone is a sensitive instrument that converts ground motion into an electrical signal via a
magnet suspended within a coil on small springs. The data collected by the geophone, such as the footsteps of pedestrians on
the pavement, were then converted into sound and played back through an audio system in real time. This allowed workshop
participants to have both a visual and audio illustration of the vibrations recorded by the geophone.

335 The second method of data collection involved the installation of a Nanometrics Trillium 120 PA 3-component broadband
seismometer, connected to a Taurus datalogger in the WMB tower (Fig. 1), to monitor the response of Great George not only
to the activity in and around the building but also to signals from much farther distances. Such instruments are routinely
deployed at seismic stations around the world and are used to monitor the Earth's seismic activity. This station was given the
name GT01 and will be referred to as such in the figures that follow. A broadband seismometer allows for the accurate

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recording of seismic data (vibrations) in a broad range of frequencies, which is ideal for capturing the variety of signals reaching the tower. The 3 components of the seismometer record ground velocity in 3 orthogonal directions: East-West (HHE), North-South (HHN) and up/down or vertical (HHZ). The seismometer collected data at a rate of 100 Hz (100 samples per second) which effectively captures signals with frequencies up to 50 Hz. At the low end, the instrument is sensitive to frequencies less than 0.01 Hz, or greater than 100 seconds in a period. These data were recorded intermittently between 23 March 2018 and January 2019 and several interesting signals have been extracted from the data including the magnitude 4.2 Lincolnshire, UK earthquake that occurred on 9 June 2018. The seismometer also recorded many distant – so-called teleseismic – earthquakes that occurred many thousands of kilometres away from the UK. In addition, several other noteworthy observations have been made. These include differences in signal recording between night/day and weekday/weekend, variations in signal amplitude measured on the vertical and horizontal channels, and differences between the recordings made on the seismometer in the tower and other seismometers that were running on a lower floor of the Wills Memorial Building.

2.1 Signals from the bell ringing

On most days, Great George rings hourly by the action of an external clapper striking the exterior of the bell. The sound produced by this ringing can be heard as far as 1.6 km (1 mile) away; the maximum distance at which the bell can be heard extends up to 20 km (12 miles) (Ringing For England, 2019) when the internal clapper is used on special occasions. The seismic signal produced by the ringing of the bell stands out from the background activity around the tower because it is produced by a source that is near the tower seismometer. The signal also contains a distinctive set of frequencies, which gives the bell its recognisable sound.

There are a number of ways of visualizing seismic data; commonly, signals are displayed in the time domain where changes in amplitude of the waves are shown as a function of time (e.g. Fig. 3). Another method of visualizing seismic data is to display the signal in the frequency domain – here, the amount of energy in a frequency band is shown as a function of time. Such data are typically presented in a spectrogram as is done in Fig. 4, which represents the energy in each frequency band as a colour; warmer colours indicate stronger energy.

Figure 3 shows a day of data recordings on all 3 components of the seismometer. These recordings were made on 23 May 2018, the University Charter Day when the bell was rung by a group of bell ringers (see time lapse video of the bell and Charter Day bell ringing: <https://vimeo.com/317784573> accessed: 08/04/2020). The regular bell chimes are less than half the amplitude of the Charter Day bell ringing which occurs at roughly 12:50 PM; the internal clapper produces a much louder sound than the external clapper. A zoomed-in view of one of the bell chimes (Fig. 4) shows that the individual chimes are visible in the data; there is also a low amplitude signal, most visible before the first chime, created by the grinding motion of the external clapper leaving its housing to strike the bell.

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2.2 Variations in activity levels near the tower as a function of time

In addition to the signals produced by the ringing bell, three noteworthy features are striking when looking at a full day of activity near the tower. First, the station is always recording activity – the area is never quiet. The tower sits along one of the major thoroughfares into and out of Bristol city centre, including an often-used route to and from the Bristol Royal Infirmary (hospital). Second, the data show a marked difference in activity near the tower during the day as opposed to the night-time. And third, there are several more hours of overnight activity on the weekends compared to a typical weeknight; this is somewhat different from the observations of Díaz et al. (2017) who note generally quieter weekends in their study. Figure 5 shows two days of activity, presented as one hour of data in the time domain per line (much like an old fashioned helicorder). The data for Thursday (14 June 2018, 00:00 UTC to 15 June 2018 00:00 UTC) (Fig. 5a) shows that there are fewer bursts of activity in the early morning hours than there are later in the day starting at about 5 AM UTC until ~ 22:00 UTC. Figure 5b shows activity recorded from 12 AM UTC on 16 June to 12 AM UTC of 17 June, which was a Saturday. There is more activity late into the Saturday night and early in the morning following Friday night.

Figure 6 displays the same data presented in Fig. 5 as a spectrogram. Again, both figures show higher amounts of energy/vibrations recorded during the daytime hours starting at about 6 AM and continuing throughout the day until about 10 PM at night on a typical weekday. They also show that this period of heightened activity extends almost 24 hours on the weekend. This is particularly clear on the condensed seismogram displayed above the two spectrograms. These examples confirm what we already know, namely that there is more activity in a city centre during work hours and also late at night on the weekends; however, the recorded data also evidence the extent to which our cities are never silent, existing as environments continuously animated by ground vibrations. A notable departure from this constant hum of activity comes in the wake of the 2020 COVID-19 related lockdowns. The nearly global stay-at-home orders have resulted in a corresponding global decrease in seismic background noise levels. In Brussels, Belgium, for instance, the reduction in background noise is such that in some cases, seismic events at the same high-frequency levels as the background noise can be detected and surface stations have the same signal quality as borehole stations buried at depths of 100 metres (Gibney, 2020).

2.3 Regional and teleseismic earthquakes

During the ~1-year deployment of a seismic station in the WMB, several earthquakes were recorded from distant sources. Many of these occurred along plate boundaries, where tectonic plates collide, separate or slide past each other. Here we discuss an event from Indonesia, in which strike-slip faulting and the ensuing tsunami resulted in significant damage. We also show an event from Greece, where the plate boundary is more diffuse, but still leads to large earthquakes. Finally, we consider events from Hawaii, recorded during an eruptive sequence of Kilauea Volcano. Here, the mantle is upwelling in a plume-like structure, forming the chain of Hawaiian Islands. But first, we consider an earthquake much closer to home, which occurred on an ancient

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415 fault that is still settling down in response to the retreat of the large glacial sheets that once covered the British Isles.
Cumulatively, these signals document the voice of a restless planet.

When an earthquake occurs, it releases energy in the form of seismic waves which radiate away from the earthquake source in all directions. This energy can be picked up by seismometers because they are highly sensitive instruments capable of measuring vibrations not only in the immediate vicinity of the instrument, but also from regional and teleseismic distances.
420 What distinguishes a regional from a teleseismic event is a bit arbitrary, but generally, teleseismic events are considered to be those that occur at distances greater than 1000 km and regional events are closer. Charles Richter (1935) established an empirical magnitude scale for assessing the size of local seismic events (abbreviated (M_L), defined as those closer than 500 km from a seismic station. There are several magnitude scales in use today, but Richter's local magnitude scale is among the most commonly used. When describing the size of larger seismic events (magnitude 4 and above) it is more common to use
425 the moment magnitude scale (abbreviated M_w) which is based on an assessment of the work (force times distance) done during earthquake rupture (Hanks and Kanamori, 1979). Where possible, seismologists prefer to use the M_w scale over the M_L scale, as the former is directly related to physical processes (i.e., the slip on a fault area in rock of a given strength) (see, e.g., Kendall et al. (2019)).

430 An example of a local or near-regional earthquake was recorded by the tower seismometer on 9 June 2018. This magnitude 4.3 earthquake occurred near Grimbsy, in Lincolnshire, UK. Signals from regional (or teleseismic) earthquakes look very different at distant stations than they do at stations near the source (compare the images in Fig. 7). As a seismic wave propagates through the Earth, its signal gets weaker and weaker as the seismic wave spreads out – this is known as spherical divergence or geometrical spreading. Furthermore, the Earth acts as a natural filter, absorbing high-frequency energy. The ability to
435 distinguish these signals from the background noise at distant stations often requires the application of a filter to remove cultural noise like that seen in Fig. 6 in the frequency range of 5-20 Hz. For most of the distant earthquakes recorded in the tower, a filter of 0.1 to 1 Hz was used, which is in a range well below the dominant cultural noise from traffic, people and machinery.

440 The seismic signal recorded near the Lincolnshire earthquake clearly shows the onset of the seismic wavetrain at station LMK, which is located near Market Rasen, Lincolnshire, England, UK (latitude 53.4573N, Longitude 0.3274W), ~ 5 km away from
the earthquake epicentre. Seismic signals from an earthquake are comprised of many so-called phases. The clearest distinction to make is that between the first arriving P-wave, which is a wave that propagates as a series of compressions and rarefactions, and the later arriving S-wave, which propagates as oscillations transverse to the direction of wave propagation. The P-wave
445 and S-wave arrivals are clearly visible at station LMK, with the P-wave primarily visible on the vertical component of the seismometer (HHZ) and the S-wave visible on the two horizontal components (HHE and HHN). In contrast, the signal from

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this earthquake recorded on GT01 in the WMB tower is much weaker in amplitude; the signal recorded on GT01 is about 1/10th the amplitude of that recorded on station LMK. Furthermore, the onset of the P-wave and S-wave is much less clear.

The Lincolnshire event was relatively small compared to several other large and devastating earthquakes that occurred in 2018. As indicated above, Richter's original magnitude scale is only appropriate for local events, so instead, these large events are reported in the moment magnitude (M_w) scale. One such event was the 28 September 2018 magnitude M_w 7.5 Palu, Indonesia earthquake which resulted in significant loss of life and property. It was the deadliest earthquake of 2018, and the earthquake and resulting tsunami and mudflows led to ~~the~~ estimated death of ~~more~~ than 4340 people, over 10,000 injuries and the destruction of over 70,000 homes (Goda et al., 2019).

Although this earthquake was almost 110° (over 12,000 km) away from Bristol, the seismometer was able to detect the earthquake over 14 minutes after it occurred (Fig. 8). What was a national disaster and a source of human loss in a developing nation, was only perceptible on sensitive seismic instruments in the UK. More poignantly, an equivalent sized earthquake in Japan would likely not lead to any loss of life. Whilst Japan and Indonesia experience large earthquakes every year, as they lie on the boundaries between tectonic plates, Japan has the money to engineer and construct earthquake resilient buildings and infrastructure.

When examining data from distant, large earthquakes, early researchers (Oldham, 1906; Mohorovičić, 1910; Jeffreys, 1926; Lehmann, 1936) could identify simple arrivals from P and S-waves, but they could also see other arrivals as seismic energy propagated and reverberated within the Earth. Some of these additional phases (Pdiff, SP, PKKP, etc.) can be seen in Fig. 8 and Fig. 9. The first signal to arrive at GT01 is the P-wave (Pdiff) that transits the Earth's mantle and diffracts along the core-mantle boundary, which lies nearly 3000 km below our feet. Others that are visible include those that interact with the Earth's core – for example, PKKP, is the P-wave that travels through the mantle and outer core, reflecting once off the underside of the core-mantle boundary, before reaching the seismic station. Figure 9 shows the paths of various seismic phases that travelled from the site of the earthquake, denoted by the star at 0° to the station in Bristol, over a quarter of the way around the planet. Here, we only show the phases that are most easily visible on the seismogram in Fig. 8 but it should be noted that there are other less-easily visible phases present in the seismic trace; there are ~~many~~ current research endeavours to study these more exotic signals. Teleseismic events such as this one provide our primary means of mapping the internal structure of the planet; they are how we know, for example, that the Earth has a core that is distinctly different from the mantle.

Seismic waves travel through the Earth like light travels through a prism; as the waves cross layers they encounter variations in material properties, which cause them to bend/refract, reflect or even change phase (e.g. P-waves convert to S-waves). Analysis of these changes in the seismic waves highlights the existence of the main layers within the Earth such as the solid inner core, the liquid outer core, the mantle and the comparatively thin crustal layer upon which life exists. The arrivals from

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an event such as the Palu earthquake, which occurred at a relatively shallow depth of ~20 km, illuminate the existence of the inner and outer cores when waves reflect off the inner core and either pass through or are diffracted off the outer core. Modern-day seismologists use arrivals from many earthquakes recorded by dense seismic networks to tomographically image the Earth's three-dimensional internal structure, much the same way as medical imaging techniques are used to investigate the internal structure of the human body.

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Closer to home, the magnitude M_w 6.8 that occurred approximately 44 km SW of Mouzaki, Greece on 25 October 2018, had far fewer devastating consequences. Like the Palu event, this earthquake also registered on the tower seismometer and its signal is visible above the regular activity near the tower (see Fig. 10). Although smaller and less destructive than the Palu event, the Greece event occurred closer to Bristol and was therefore more apparent in the raw waveform data. Data from this earthquake also provide a treasure trove of information on the internal structure of the Earth. The P-wave and S-wave arrivals are clearly visible phases that travel through the Earth's interior and are therefore referred to as body waves. The larger energy arriving after 1000 seconds is associated with surface waves that propagate along the surface of the Earth. Surface waves are always slower than body waves and are generally lower in dominant frequency.

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2.4 Variations in signal amplitude due to local site effects

The amplitude of the seismic signal is a direct measure of the strength of vibrations affecting the seismometer. Signals that are produced by the horizontal motions of the ground or wind should produce a stronger signal on the horizontal channels (HHE and HHN) than they would on the vertical channel (HHZ). Likewise, signals produced by the vertical movement of the ground beneath the tower should produce a stronger signal on the vertical channel than they do on the horizontals. A look at the data from the tower (Fig. 11) shows that many of the signals recorded have higher amplitude on the vertical channel than they do on the horizontals. This is somewhat surprising since the expectation prior to the launch of this experiment was that the natural sway of the building, coupled with the impact of strong winds, would have greater effect on the horizontal channels than it would the vertical.

At various points during the period that the seismometer was installed in the tower, there were other seismometers recording in the Wills Memorial Building. Comparison of the data from these seismometers to that recorded on the tower seismometer showed that the signal in the tower was being amplified on all channels. This is not surprising as shaking is expected to be amplified in tall buildings, particularly when they are impacted by low frequency shaking that match their resonant frequency. A building's resonant frequency is approximately inversely proportional to its height (Pratt et al., 2017). An example of this signal amplification is shown in Fig. 11; here, the traces are filtered between 2 and 10 Hz to separate the earthquake signal from the background noise. This figure shows a comparison between the signals recorded from the Lincolnshire earthquake discussed above as recorded by a seismic instrument on the first floor (one floor above the street level) and GT01 in the WMB tower. The amplitude of the data recorded in the tower is more than double that recorded on the lower level.

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2.5 How does it compare?

While the day to day "seismic" activity around the WMB seems quite vigorous, it goes largely unnoticed by the city's inhabitants. This raises questions of how Bristol's daily "seismic" activity compares to seismic signals from real earthquakes. Data recorded in the tower of both background noise and the bell peal were compared to seismic data from earthquakes of varying magnitudes recorded on stations in Hawaii. The Hawaiian earthquakes were recorded on seismic stations that were within 1 to 5 km from the earthquake epicentre. As illustrated in Fig. 12, the data from the tower are barely visible against the higher amplitude signals produced by real earthquakes. The smallest real seismic event on these plots is a magnitude 1 earthquake recorded at a station 1 km from the event. From the zoomed-in view in the inset of Fig. 12, the amplitude of the Bristol data (magenta and green) can be seen to fit neatly within the amplitude of the waveform for the magnitude 1 event (blue waveform). The Bristol data sit well below the vibrational levels of both the magnitude 3 (yellow) and the magnitude 6 (red) events. Placed in this context, it is clear why the activity in the city may go largely unnoticed. The amount of shaking produced by a magnitude 1 earthquake is seldom within the detection threshold of humans. However, as the event magnitude increases, it becomes easier for humans to detect a ground motion event in noisy settings even when the changes in magnitude are relatively small. This is because the commonly used earthquake magnitude scale is a measure of the amplitude of ground displacement and is logarithmic; this means that an increase of 1 in magnitude equates to a tenfold increase in the amplitude of ground displacement. ~~There is also a multi-fold increase between the energy released by an earthquake and its calculated magnitude.~~ For instance, a magnitude 3 earthquake releases roughly 32 times more seismic energy than does a magnitude 2 earthquake.

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2.6 Church bells ring during earthquakes

Historical reports of earthquake activity frequently include notes on church bell peals accompanying ground shaking during an earthquake, even in situations where the bell is not proximal to the earthquake epicentre. Such incidents were reported in Charleston, SC following the 1811 New Madrid earthquake which occurred on a fault approximately 977 km away from the church (LaCapra, 2011). Likewise, the spontaneous ringing of church bells was heard as far away as Paris following the 1755 Lisbon, Portugal earthquake (Penna and Rivers, 2013). Both earthquakes in the examples above were large but it is also worth analysing the effect of the energy released on structures far away from the epicentres. The Modified Mercalli Intensity Scale estimates that bells ring with earthquake intensities of V to VI, which roughly corresponds to ~~the shaking experienced in a~~ magnitude 5 ~~earthquake near the epicentre~~. The relation between earthquake magnitude and energy can be written as

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$$\log_{10} E = 5.24 + 1.44M, \quad (1)$$

560 where E is the energy released by the earthquake and M is the moment magnitude of the earthquake magnitude (USGS Science Center, n.d.). Therefore, a magnitude 5 event corresponds to an energy release of 2.75×10^{12} J.

This calculation shows that there is a large amount of energy released by a magnitude 5 earthquake, but this number only relates to the energy released in the immediate environment of the fault that generated the earthquake. As the seismic energy propagates out from the earthquake epicentre, it dissipates; this is referred to as geometric spreading. The formula for estimating the relationship between the energy dissipation and earthquake distance is given in Eqs. 2 and 3 for surface waves and body waves (P and S phase) respectively

$$E \propto \frac{E_0}{2\pi r} \quad (2)$$

570 $E \propto \frac{E_0}{2\pi r^2} \quad (3)$

where, r is the distance from the earthquake epicentre measured in metres and E_0 is the energy at the earthquake source. The surface waves occur later in the wavetrain than the body waves and tend to be of higher amplitude (see, for example, the Greek earthquake and the signals arriving after 1000 s in Fig. 10). These waves tend to cause the most shaking and therefore, the most damage.

575 The 1811 New Madrid earthquake has an estimated magnitude range of 7.0-8.0 (Johnston, 1996; Hough, 2004; LaCapra, 2011). As an example, we can therefore estimate the amount of seismic energy that arrived in Charleston, SC. The surface wave energy reaching the city was about 6 orders of magnitude larger than the body wave energy, but was only equivalent to the energy released by a proximal magnitude 3 earthquake. Magnitude 3 earthquakes are considered weak events that cause little to no structural damage. Therefore, for ringing to occur under these conditions, other factors may have been influential.

580 For instance, church bells are often left in the "ready" position (Woodhouse et al., 2012) in which the bell is placed just beyond its unstable equilibrium position and held in place by a sliding stopper. In the "ready" position, the inertial forces that must be overcome to swing the bell are greatly reduced, which in turn also reduces the amount of ground shaking necessary to move the bell. In cases where bells are rung by the action of an external clapper, it would likely be easier to move the external clapper during an earthquake than it would be to move the bell and its internal clapper.

590 A third factor that may have influenced the ringing of the church bells during an earthquake is the amplification effect of the bell tower. Research by Blakeborough (2001) showed that while the ringing of the bell is dependent on the mechanics of the bell and the tower in which it is hung, the peak ground acceleration (PGA) typically required for unplanned ringing needs to exceed the PGA of a magnitude 5 earthquake. From our own experiment, illustrated in Fig. 11, there was at least an order of magnitude increase in amplification between the signals measured on the tower compared to the seismometer on the lower

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600 floors of the building. The signal measured in the tower was roughly double that measured on the lower floor but would not
be enough to amplify the shaking from a magnitude 3 to a magnitude 5 event. Besides the basic amplification effects of the
605 height of the tower, it is also reasonable to consider how resonance may play a role in the signal amplification. All structures
have a natural frequency at which they will vibrate when a force is applied. For buildings, this natural frequency is affected by
a number of factors such as building shape and material make up but is most strongly affected by building height; tall buildings
610 have a lower natural frequency than shorter ones. When incoming seismic waves have the same frequency as the natural
frequency of a building, the shaking that that building experiences is amplified; this signal amplification may be up to 4-5
times as strong as the original arriving wave (Arnold et al., 2006). This resonance effect has been noted to cause differential
building damage in past earthquakes; for example, during the 1985 Mexico City earthquake, the presence of soft sediments
615 from an old lake bed beneath the city caused certain frequencies of the arriving earthquake wavefront to be amplified even
though the city was 250 km away from the earthquake focus; the frequencies of these amplified signals coincided with the
natural frequencies of buildings between 6-20 stories tall (Seed et al., 1988; Arnold et al., 2006). As such, the damage incurred
by buildings in this height range was more severe than buildings outside of it. Therefore, if a similar resonance effect is
experienced by a distant bell tower, it is possible that the tower may experience more shaking than other buildings in the area
which could potentially result in unscheduled bellringing. All the above-mentioned factors may serve to increase the effect of
seismic waves arriving from great distances; hence, a number of factors could have contributed to the historical unscheduled
620 ringing of church bells reported following large earthquakes, such as that observed in Charleston following the New Madrid
earthquake.

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2.7 Transforming seismic data into art

620 Monitoring ground shaking and earthquake activity is mostly the job of scientists and researchers, whose areas of expertise
connect with the distant global environment. And for those who live near an area that directly experiences the Earth's tectonic
activities, the contact is only too real and impacts daily lives. But for many where this impact is not usually felt or experienced,
being made aware of the constant noise and movement occurring under our feet can be surprising. The creative aspect of this
625 project thus experimented with performance in order to encourage public engagement with the energy, force and distant origins
of particular sources of sound; onlookers and audiences could fast track the "scientific explanations" of the unsettled Earth's
activity and instead perceive it in a direct and visceral way. After hearing recordings captured during the ~1-year deployment
of the seismic station in the WMB, for example, the choreographer Will Pegna was inspired to create a durational dance piece,
All Terrain Training, performed in Peckham in an artist-led space. A photo captured during one of the acts of this performance
is shown in Figure 13. The particular source of the recordings in this case came from a M_w 7.4 earthquake on 28 September
630 2018 near Sulawesi Island, Indonesia which is ~12,200 km from Bristol and a M_w 7.9 on 6 September 2018, near Viti Levu
Island, Fiji, ~16,000 km away. These recordings were amplified and mixed live for the event by Shirley Pegna. To convey the
power of the low audible and the low inaudible vibrating frequencies, the cone of a 22-inch subwoofer was employed along

635 with speakers to create a surround sound and immersive effect for the audience members (see subwoofer cone vibrating: <https://vimeo.com/389225640> accessed: 08/04 2020). A second performance piece was also made, inspired by the earthquake sounds mentioned above. This piece, *Earth Din*, presents these sounds via three subwoofers and four speakers placed in a large space where an audience can walk around amongst the speakers and be immersed in the sound and vibration. To create further interest by embellishing the experience of the natural sound, the piece also requires two musicians intermittently playing cello and double bass. The two musicians work with the sounds, reacting to them and each other in the moment, and improvising the sounds they add to the soundscape. The sharing of the sound and vibration from our planet to an audience via both these expressive performances thus creates another way to experience the Earth activity data recorded from the Wills Memorial Building tower.

645 We found that the set of vocabularies we have for size, scale, distance and time need~~ed~~ to be re-imagined, processed and re-assessed when contemplating the vastness of the Earth, particularly by those of us not used to thinking in this way. With this in mind, the third artwork coming from the ideas raised by this interdisciplinary project dealt with temporality, exploring the notion of geological time. The birth of planet Earth, its existence, and its projected demise spans a very different duration compared to our quodidian experience of the day to day. Shirley Pegna's *The Rock Record*, an object for a conceptual artwork, plays on the term used in geology to refer to the stratigraphic record that denotes how geologic time is captured in a rock sequence, and is in this case a rock into which is etched sound wave data from the recordings captured from the WMB. The seismic data recorded by the seismometer is first converted into a sound file, and in the same manner by which sound waves of music are etched into copper plate in the process of pressing a vinyl record, the etching we are currently creating will sit embedded in a record (LP) not made of vinyl but of very durable rock. Even this token design copy of a contemporary media player will outlast the 21st century objects made of degradable vinyl, wood and plastic and possibly outlast even the span of human existence in rock form. In theory, it may even last into geological time itself.

The various art installations and performances that have resulted from this project demonstrate how people view everyday rumblings and vibrations of the ground beneath our feet, but also give insights into how we view the more catastrophic nature of large earthquakes. Audience members were asked for feedback after the *All Terrain Training (ATT)* and *Earth Din* performances. We also gathered observations from people who experienced ground noise recorded by a geophone and amplified through a subwoofer (the *Ground Sound* and *You Are Here* projects – see shirlypegna.com), as also demonstrated during our one-day public workshop.

665 In general, the projects were well received and stimulated a diverse set of personal experiences. Nevertheless, there are some common threads through the remarks. To capture this, a summary of the comments from performers, participants and audience members is presented through a word cloud (Fig. 14). The most commonly occurring words are *sounds, feel, audience, space*

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and, *Earth*. As a first observation, the feedback shows how the art projects facilitate engagements with the wavelike nature of sound and ground motion; through touch and hearing we sense this interrelationship in the physics of wave propagation.

Another common theme concerns togetherness, or a shared human experience with planet Earth, and registers an ecological awareness that is simultaneously both connective and disquieting. As one of the dancers in the *All Terrain Training* performance observed: "*The intense atmosphere that was created by the use of sound and movement together, as well as the awkwardness created by the closeness of the audience to the dancers, really struck me as being an accurate representation of the relationship between humans and the planet*". Furthermore, an audience member noted that "*ATT showed us how important it is for us to push against each other as people and find unity and harmony within that push. The work was moving and reminded us of how to remain human*". Others who attended the Ground Sound installation said: "*We leave a heavy footprint even though we don't mean to*"; "*I will walk more softly from now on*". Both reflections are poignant reminders of our influence on the planet.

The feedback also demonstrates that how we react to ground motion is a very personal experience, and can vary widely between individuals. Some found the performances comforting: "*Love that sound*"; "*Very comforting*", whilst others found them unsettling: "*Spooky – Scary*"; "*Made me feel ill*". Some found the immediacy of the listening experience exciting: "*Brilliant – Noisy isn't it?*", while for others it evoked memories of previous embodied experiences. Particularly striking is the use of simile – a figure of speech that looks for resemblance – in the responses to *Ground Sound*: "*Like boat engines in the dock*"; "*Like under water*"; "*Like being a child again – car trip with your parents – being on the back seat*".

The projects made people think about the unsettled nature of the Earth and question its cause ("*Was it the trees and the roots (making the sound)?*"). As an audience member at the *All Terrain Training* commented: "*The field recordings were disorientating to the ear, but seemed to balance perfectly against the dancers pressing together like tectonic plates*". Interestingly, the performance also captured just how unsettling it can be to experience an earthquake, even within mediated terms as the comments of a dancer reveals: "*... all-encompassing sound [...] gave dimension to the space, blurring our understanding of what was close and far away. The haphazard speed of the sounds left an unexpected nature to which you could not expect what was coming next*".

Through these experiences, audience members and performers could derive a sense of uncertainty associated with experiencing an earthquake (how will I react? how bad will it get?). But their responses also demonstrate some of the challenges inherent in earthquake hazard awareness and preparedness. As one audience member said: "*The voyeuristic nature of the performance would break once the performers pushed themselves into the crowd, activating the audience to move or become a part of the performance itself*". In some ways, people are like this with natural disasters. What is initially an interesting or entertaining thing to watch, quickly changes when you experience it first-hand and become part of it. This work shows how performance

art can be used to better appreciate and communicate our connection with the Earth, while also improving our awareness of natural hazards such as earthquakes.

3 What determines how people respond to ground shaking?

720 As discussed above, the Earth is constantly moving and vibrating around us though this motion is a frequently accepted part of our daily lives and often ignored. This general acceptance of ground motion leads to the question of what determines human responses to Earth vibrations. The eventual acceptance of the theory of plate tectonics, some fifty years ago, ushered in a new scientific paradigm that explains the driving forces behind earthquakes (McKenzie, 1977; Oreskes, 1999). The Earth through its frantic effort to cool itself through convection and conduction, has created and destroyed entire tectonic plates many times through its history. However, at various points throughout our human history, earthquakes have played a central role in human thought and development. From early ideas concerning punishment or exercise of divine wrath, to the facilitation of dynastic changes to enable modernisation, earthquakes have been explained through folklore, religion, and philosophy (Winchilsea, 1669; Mallet, 1728; Ponton, 1872). The Great Lisbon Earthquake of 1755 is a famous example of an earthquake accelerating divisions between religion and science, leading thinkers and poets to question the benevolence of a divine god. Indeed, as 730 Juengel (2009) summarises, "Lisbon has of course long loomed as the world historical event that cracked the foundation of Enlightenment optimism, driving Voltaire to abandon Leibniz, Pope, and the rightness of what is and to embrace Bayle's more profound doubt" (see also Nichols (2014)).

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For historical earthquakes from the "pre-instrumental era" prior to the last decade of the nineteenth century, the only method of study is to use intensity, which is a number quantifying the degree of shaking at a particular point. In the case of the earthquake of 6 April 1580, for example, which was felt throughout a large portion of England, northern France and the Low Countries, and is now thought to have had an epicentre in the Straits of Dover, a rich multi-lingual textual record of sources, including letters, new pamphlets, prayers, treatises and even satires, bears witness to the effects of the shock (Neilson et al., 1984). These sources include not only vivid literary responses to the earthquake, all the more fascinating for the different 740 generic and ideological frameworks through which they are presented, but also document the particular effects felt in specific locations, from falling masonry, to bells ringing, and theatres shaking (Totaro, 2017). In his discussion of the event, the physician and translator Thomas Twyne (1580) wrote of how "the very shaking caused the bells in some steeples to knoll a stroke or twain", and that "the tops of half a dozen chimneys in London were cast down". As someone who did not feel the ground moving personally, he was keen to address how not everyone felt the effects of the earthquake equally:

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745 Some that were above in their chambers, commonly judged that some violence had been done to their houses beneath. Some that remained below, found fault with tumbling and trampling above. Some imputed the rattling of wainscots to rats and weasels: the shaking of the beds, tables, and stools, to dogs: the quaking of their walls to their neighbours rushing on the other side. And as their opinions were sundry, so were their speeches thereupon diverse, until a

755 common conference being had, they were resolved upon their common case and danger. For many not trusting to
their own judgement, and partly also moved with fear, ran out into the streets to know if the like had happened unto
others.

760 Twyne's contribution to the literary record of the 1580 earthquake is noteworthy owing to the way it captures the reactions of
ordinary people and how they speculated about the causes of the ground shaking, looking first to everyday explanations for
felt motion, and then, having realised the novelty of the occurrence, to a kind of community consensus in order to understand
more fully the scale and nature of what has happened. As Neilson et al. (1984) have shown, where multiple testimonies of this
kind exist, details concerning felt effects at particular locations can be used to create intensity maps, and to estimate the focal
depth and magnitude of events, in this particular case resulting in an estimated Richter magnitude in the range M_L 6.2-6.9.

765 From the perspectives of the humanities, then, responses to the ground moving can be seen to be determined by how lived
experiences are processed and understood within pre-existing cultural, theological, linguistic, philosophical and narrative
frames. In historical reports it seems to matter whether the right language can be found to articulate the experience of the
ground shaking, and this can often involve analogy in order to communicate the precise nature of the sensations experienced,
which can then be likened to a cognate encounter of unsteadiness or vibration. Perhaps more importantly, the use of literary
genre to construct a deliberate interpretative frame asks us to consider how genre gives shape to different kinds of temporal
relationships and possible endings, owing to how genres can be used to determine narrative expectations by connecting
causality, action and consequences in particular ways. In Europe, representations of earthquakes have been historically framed
not only by tragic modes which speak of hubris, divine retribution, and even apocalypse, but also through providential models,
including those of recuperation, where the earth quaking takes on the significance of a divine admonition, calling the faithful
both to repent and to give thanks for their deliverance. These literary and theological frameworks co-exist in generative ways
770 with local folklore, eye witness testimony, and the rationalisations of science, which in Europe, from the late sixteenth-century
onwards, grew out of the narrative methods of natural philosophy and drew on the authority of classical treatments of
earthquakes and their causes by writers such as Aristotle and Lucretius (Prewitt, 1999; Passannante, 2008). In early modern
Europe, c.1500-1800, surviving textual responses to natural disasters also reveal active transnational networks of printed news
– an early version of our contemporary rapid mediation of such phenomena – and the ways in which environmental events,
775 including floods, volcanoes, and earthquakes, could be used for political ends, prompting the state-authorised publication of
guides for public worship (Mears, 2012; Caracciolo, 2016). The historical records of natural disasters are also useful for dating
literary works. The composition of William Shakespeare's *Romeo and Juliet*, for example has traditionally been calculated on
the basis of an earthquake reference made by the character of Juliet's Nurse (Thomas, 1949; Dodson, 1950).

785 To write in response to catastrophe, then, is to engage imaginatively with the limits of human reasoning and to formulate
representational, and aesthetic, modes capable of handling epistemological change (Heringman, 2003). As Totaro (2017)
observes of the 1580 event, "the earthquake imprinted the body-mind and altered all other sensory-related terrain immediately":

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a reaction ~~that~~ transformed the event into "a subject of epic proportion". To connect the scale of the earth quaking to the epic mode is perhaps to consider what it takes for a culture to live and rebuild in the aftermath ~~of natural disaster~~; yet, for writers of the eighteenth ~~century~~ responding to the Lisbon earthquake of 1 November 1755, the magnitude of the destruction was connected to the sublime. As William F. Fleming (2005) writes, summarizing the hitherto unparalleled scale of the ~~initial~~ event ~~and subsequent cascade events~~, "within the space of five or six minutes, at least thirty thousand people died; the city was reduced to ruins, and the earthquake itself was accompanied by fire and the flooding of the Tagus River". The poem written by the French Enlightenment writer Voltaire (see Voltaire and Fleming (2005)) in response to the calamitous events responds to the mutable, tremulous nature of the Earth, and includes the author's struggle with the long-held but now newly troubled idea that we live in the best of all possible worlds:

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I can't conceive that ~~"what is, ought to be,"~~
In this each doctor knows as much as me.
We're told by Plato, that man, in times of yore,
Wings gorgeous to his glorious body wore,
That all attacks he could unhurt sustain,
By death ne'er conquered, ne'er approached by pain.
Alas, how changed from such a brilliant state!
He crawls 'twixt heaven and earth, ~~then~~ yields to fate.
Look round this sublunary world, you'll find
That nature to destruction is consigned.

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For Jörg Trempler (2013), the Lisbon earthquake not only ushered in a "new condition", owing to how the long-held "philosophical tendency that regarded the world as the best of all possible worlds" suddenly "found itself incapable of explaining away the destruction of a capital city", but also prompted the invention of "catastrophe" as an iconographical tradition. In the transient world figured by Voltaire it is the fate of contemporary humankind to walk or merely "crawl" upon the earth, rather than to be raised above it, and to be subject to the shaking, impermanent motions of a "sublunary" existence.

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The impact of the earthquake, as addressed in such terms, was to reveal the sublime power of nature's latent destructive capacity. Indeed, to narrate "catastrophe", as Juengel (2009) observes, is thus to confront the "telltale shuttling between measure and melancholy" that "structures the epistemological work of the postdisaster". As he explains, "the word catastrophe already possesses its own strophic or figural quality, for etymologically the term's Greek origins signal an ~~overturning~~ of the order of things; thus ~~'catastrophe'~~ becomes what we name a suffering heretofore unthinkable".

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A similar scaling of response, used to confront the "unthinkable", is seen when comparing large earthquakes between regions in modern society. In general, people living in earthquake prone areas in developed countries like Japan tend to be more comfortable with large earthquakes than those living in developing but earthquake prone countries like Haiti. This relative comfort is imparted by confidence in the engineering and disaster management in place in developed countries (Kahn, 2005).

835 However, this confidence can potentially be a double-edged sword leading to complacency which may result in significant
loss of life and resources as illustrated in the aftermath of the 2011 Tohoku earthquake (M_w 9.0 – 9.1). The ensuing tsunami
led to the destruction of the Fukushima Daiichi nuclear power plant and a subsequent moratorium on nuclear energy in Japan
amongst other regulatory changes. In the less developed country of Haiti, the 2010 M_w 7 earthquake affected over 2 million
people, damaged 80-90% of homes near the epicentre and had a death toll of well over 200,000 people (DesRoches et al.,
2011; Rebekah Green and Scott Miles, 2011). The impact of the earthquake in Haiti was likely due to two main causes; unlike
840 Japan, Haiti's economy precludes the necessary level of engineering and disaster preparedness to minimize earthquake damage.
Additionally, while a similar magnitude earthquake had struck the country in 1945, the memory of that prior event had most
likely faded from the collective memory leading to an underestimation of the disaster potential. We are left, then, with the
idea, as Fountain and McLaughlin (2016) observe, that "there are no purely 'natural' disasters. Once a hazard phenomenon –
flood, drought, tsunami, earthquake, typhoon/ hurricane, geothermal activity, or other catastrophe – intersects with human
845 society, any purported naturalness dissolves. All disasters are enmeshed in human worlds involving economic, cultural,
political and religious concerns".

In recent years, humans have also become acutely aware that their activities and interactions with the sub-surface of the Earth
induce earthquakes, sometimes in magnitude at dangerous levels. However, human acceptance of such *induced seismicity* is
850 variable, depending on the contexts within which such activities occur, which are shaped by familiarity and economic goals.
On one hand, the United Kingdom has experienced coal-mining induced earthquakes since the Industrial Revolution and the
start of large-scale underground mining (Redmayne, 1988; Wilson et al., 2015). On the other hand, much smaller induced
earthquakes have paralyzed the petroleum industry's efforts to produce domestic gas from shale formations in places such as
Preese Hall near Blackpool in Lancashire. Ground motion associated with a stadium concert or sports events can be as large
855 as that associated with sub-surface activity (e.g., fracking), but the latter causes far greater alarm. Indeed, induced seismicity
associated with fracking has proven to be very controversial, especially in the United Kingdom. During the fracking process,
large volumes of high-pressure water are injected into deep rock formations that contain gas trapped in an impermeable matrix.
The water stimulates a fracture network through the generation of tiny earthquakes – the energy produced by these small
earthquakes is roughly equivalent to dropping a book (British Geological Survey, 2008). However, in rare cases, the water
860 interacts with large pre-existing critically stressed faults. This water-fault interaction in turn leads to the generation of larger
and felt seismicity. Such was the case in April 2011 when a M_w 2.3 was triggered in Preese Hall which led to an 18-month
suspension of shale gas production in the United Kingdom (Clarke et al., 2014). It should be noted that this induced earthquake
occurred at a depth of 3.6 km and would have only produced surficial ground motion of slightly higher amplitude than a train
crossing a viaduct (see Horleston et al. (2013)). When operations resumed in a nearby site (Preston New Road) in 2019,
865 exploration was subject to a very strict traffic light system. Within this traffic light system, following a magnitude 0.5
earthquake, the operator is required to halt any further injection, reduce pressure in the system and monitor for any new
seismicity before operations may potentially resume (Oil and Gas Authority, 2013). On the 26 August 2019, hydraulic fracture

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stimulation near the Preston New Road site in Lancashire triggered a M_L 2.9 earthquake, again leading to a moratorium on fracking in the UK (Kettlely et al., 2020).

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In contrast, fracking has led to much larger earthquakes in Canada (up to M 4.1 in Fox Creek, Alberta (Schultz et al., 2017)) but there is a far less restrictive traffic light system in place in Canada and perhaps lower public concern. The difference in reaction may be threefold: a) Albertans are much more accustomed to the petroleum industry, as for many it is in fact their livelihood; b) the region where shale gas activity is taking place in Canada is less populated than Lancashire; and c) there is natural seismicity of similar magnitude in this part of Alberta, providing residents with a measure of familiarity with this level of ground shaking. The occurrence of large induced earthquakes is not solely associated with fracking. There are numerous anthropogenic causes of seismicity including mining, oil and gas activity, water impoundment via dams and weirs and geothermal energy production (Foulger et al., 2018). While these activities normally lead to minor amount of micro-seismicity (earthquakes less than M_w 2.0), there are notable exceptions. For example, in 1967, the construction of the Koyna hydroelectric dam in India led to M_w 6.6 earthquake (Berg et al., 1969; Gupta et al., 1969). Oil and gas activity in Uzbekistan led to a M_w 7 event in 1976 (Foulger et al., 2018). Recently, the American state of Oklahoma has seen a dramatic rise in seismicity which is attributed to sub-surface wastewater injection associated with oil and gas extraction. Here, the largest events were greater than magnitude 5 and led to damage to several homes and businesses as well as a few injuries (Keranen et al., 2013).

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4 Closing Thoughts

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During the final stages of writing this paper, COVID-19 reached the UK and we all went into a period of extended lockdown and isolation. As everyone stayed at home, except those providing essential services, the anthropogenic noise in the country dropped to levels not experienced in decades. In addition to traditional journal sources (e.g. Gibney (2020); Lecocq et al. (2020)), seismologists across the world have been sharing on social media visual graphics that illustrate reductions in seismic noise across most seismic networks. Figure 15 is one such example, produced by Dr. Stephen Hicks at Imperial College in London. It shows the seismic noise on two UK networks (BGS and Raspberry Shake), comparing levels before and after lockdown. It also shows correlation with UK retail and recreational activity.

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The British Geological Survey (BGS) operates a dense network of seismic stations, using instruments similar to those we deployed in the Wills Memorial Building. These stations are deliberately deployed in quiet settings. Nevertheless, a clear drop in background noise is visible starting in late March 2020 (Fig. 15). In recent years, seismometers have been deployed that cost a fraction of the price of conventional seismometers, but with only a slight degradation in instrument sensitivity. The Raspberry Shake instrument (raspberrypshake.org) is a very popular example. Unlike the more conventional seismometers, many of these instruments use a MEMS (Micro-Electro-Mechanical Systems) sensor which fits on a small chip thus reducing their size and cost relative to more traditional seismometers. Their use is a good example of citizen science in that the data are

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shared publicly so that scientists across the world can use the information recorded. They are deployed in people's living rooms, sheds, etc. and there are currently more than 50 Raspberry Shake seismometers in operation in the UK (raspberrysake.net, 2020). The majority of the Raspberry Shakes deployed in the UK are geophone-based sensors that have been electrically modified to give a response of 1-40 Hz. Figure 15 shows how the seismic noise dropped on both networks, but especially the Raspberry Shake network, during lockdown. There are also clear variations in noise between weekdays and weekends.

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The ground beneath our feet may be unusually quiet, then, at this precise moment of writing; however, a glance at the language of recent headlines reveals that "seismic shifts" are occurring in other terms, and in forms of activity across all areas of daily life, from consumer habits and corporate culture to educational practices and the trends of global politics. Indeed, our cross-disciplinary conversations prompted an increasing awareness of how we use different vocabularies, with different resonances, to articulate the phenomena of earthquakes and how these vocabularies resonate within everyday speech. From a literary perspective, it is striking how some of the most commonly used vocabularies carry metaphorical currency, having either been absorbed into colloquial ways of speaking of non-specific adverse events, or, more complexly, tasked with operating in intrinsically figurative ways themselves, retaining the memory of an emotional, moral, biological or physical charge: aftershock; stress-trigger; rift; fault; tremor; swarm; cascade; shadow zone. The increasingly over-used idiomatic term "seismic shift", for example, used to connote conceptual change across all aspects of human experience, has been commonplace in our public discourse since the 1980s, as the Google Ngram Viewer (Lin et al., 2012) bears witness (see graph linked here: <https://tinyurl.com/ydaob65o>). As Taylor and Dewsbury (2018) write, synthesising the arguments of Lakoff and Johnson (2008)'s *Metaphors We Live By* in their discussion of metaphor in science communication, "metaphors are not mere linguistic embellishments. Rather, they are foundations for thought processes and conceptual understanding that function to map meaning from one knowledge and/or perceptual domain to another". During this period of lockdown, we deploy the language of seismic activity – its shifts and its impacts – to give shape to something that we do not yet fully comprehend.

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For the project's duration, we also found ourselves drawn to a set of vocabularies related to the sonic potential of vibrations, whereby the earth can be thought to sound like a giant bell: harmonics; tones; fundamental modes; whispering gallery waves. Indeed, the bell like sonority of the Earth, our "blue planet", resembles a resonant chamber where seismic waves travel through and around its interior. The comparison is made with the Whispering Gallery in the roof of Saint Paul's Cathedral, where sound waves are reflected horizontally round the walls circle, and bounce around multiple times because the angles involved are so slight (Fitzgerald, 2016). Interestingly, seismic phases can propagate around the inside of the planet in a similar fashion, clinging to the underside of the Earth's core-mantle boundary, some 3000 km beneath our feet. Our data from the Wills Memorial Building tower at Bristol University showed evidence of seismic waves coming not only from the tower bell, Great George, and local city impact, but also extremely distant impacts travelling to the instrument from seismic activities on different continents. Our response to the data realized in sound and vibrations from the WMB tower seismometer could be

950 described as hearing "music as audible physics" (Young, 1998), where the waves travel^{ing} around the inside of the Earth are described as resounding and reverberating. ~~Reciprocally~~, such realizations can also be used to help scientists interpret seismic data (e.g., Paté et al. (2017)). Transforming earthquake signals into audible sound help^s us to better understand the scale of seismic shifts in the Earth (see, for example, <http://www.seismicsoundlab.org>).

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955 The technology, namely the seismometers and the geophone used either in, or within the vicinity of, the WMB tower to "listen in" to the ground, ~~ultimately~~ acted like bionic extensions to our human ears. Seismic waves reached the instruments from great distances by travelling through the ground, and so being able to hear and experience the waves altered our perception of what goes on under our feet and in our surroundings, by expanding the reach of our hearing and extending our ~~auditory map~~ further than the limitation of our anatomy: our planet might be unsettled but we are implicated in its motion in complex ways, our own bodies forming part of a network of sensing instruments. The ear has been described as "half anatomy and half
960 imagination", by writer and cultural critic Connor (2010), who describes how our perception of sound enhances our understanding when we can only imagine a sound's location but cannot see its source. Our technology also picked up different frequency waves, some audible and others inaudible to our ears, prompting a thought experiment to imagine what we could not hear with our human ears when perceiving seismic waves pitched below our auditory range. Yet, if we could not hear the waves as audible sound, they could still provide an impression of our surroundings. Musician Evelyn Glennie, who has a
965 hearing impairment, comments in her *Hearing Essay* that "hearing is basically a specialized form of touch" (Glennie, 2015). When we could not hear but could only feel the vibration of waves, amplified through a speaker, we were still receiving an impression of the energy coming from the earth.

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970 Connor (2010) describes sound and place as being intrinsically linked, where a "sound is the space in which it occurs" and "sonic essence inheres in spatial accident". In our discussions, we became fascinated by extending the notion that people "site" themselves in place by connecting to sound, to the idea that attending to vibrations in the earth requires people not only to "site" themselves in relation to their local environment, but also to their global environment. John Luther Adams, for example, in his work *The Sonic Geography of Alaska*, collates different elemental signals from the natural environment (Young, 1998). His reach is also global and he too states that "sound is a way of touching at a distance". From our own place of relative safety,
975 then, we re-evaluated our understanding of the ground beneath our feet and attended to what the vibrations travelling through it can tell us about the domains and limits of our situated disciplines and institutional habits. Our experiment to discern the motions of our unsettled planet, which focused on the bell Great George, thus ran alongside a second experiment, which tested novel collaborative structures of research and aesthetic practice. The result has been an unsettling of accustomed methods, stress-testing the disciplinary foundations on which we build.

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980 Data Availability: The raw data utilized in this study ~~has been~~ archived with the National Geoscience Data Centre (NGDC).
[DOI: https://doi.org/10.5285/0f7e4448-ac5f-478d-83b4-408edc244f3b](https://doi.org/10.5285/0f7e4448-ac5f-478d-83b4-408edc244f3b)

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Author Contributions: All co-authors contributed to the study and in writing the manuscript.

Competing Interests: Authors declare they have no conflict of interest.

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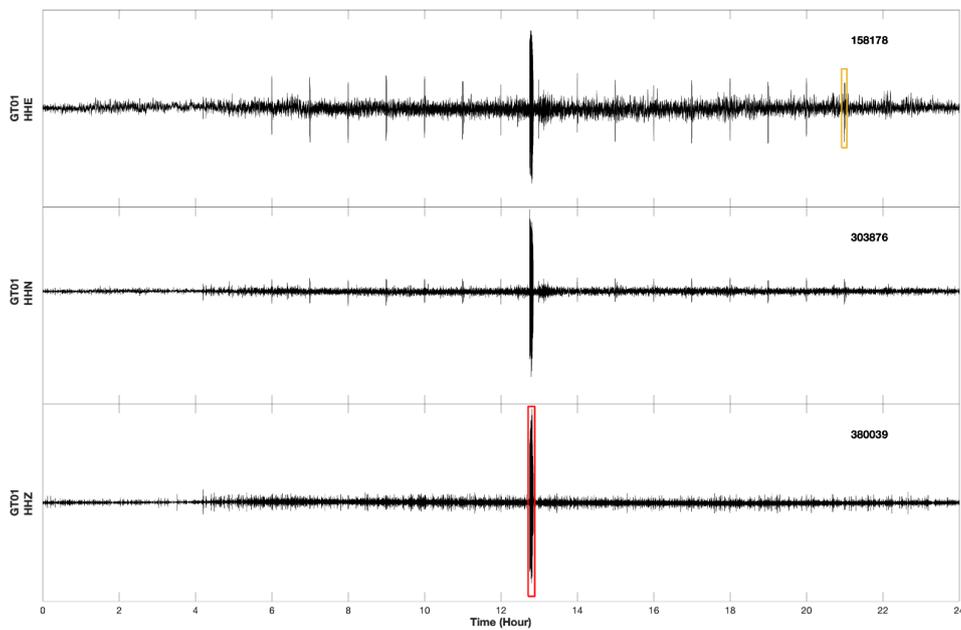
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1000 **Figure 1:** Great George Bell (b) sits within the belfry of the Wills Memorial Building pictured in (a) on a typical weeknight. The broadband seismometer (c) installation setup in one of the alcoves above the bell. The instrument itself lies beneath the black dome with the Brunel rubber duck (geophysics group mascot) on top.



Figure 2: Workshop participant jumping near geophone set up to record foot traffic near the Wills Memorial Building

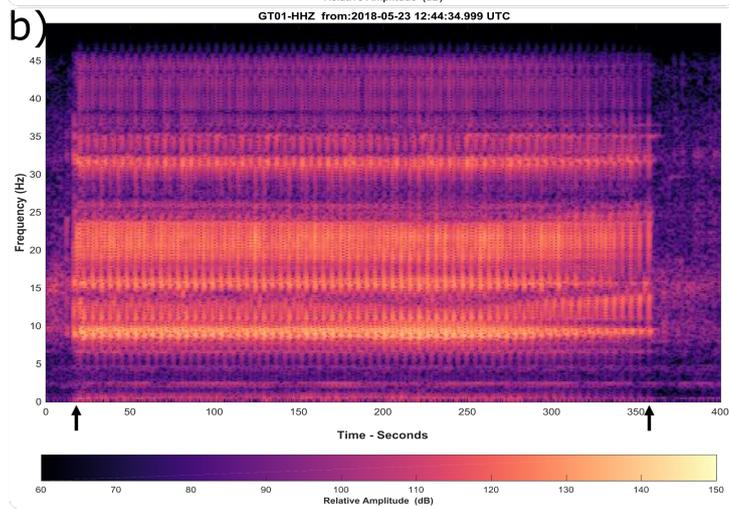
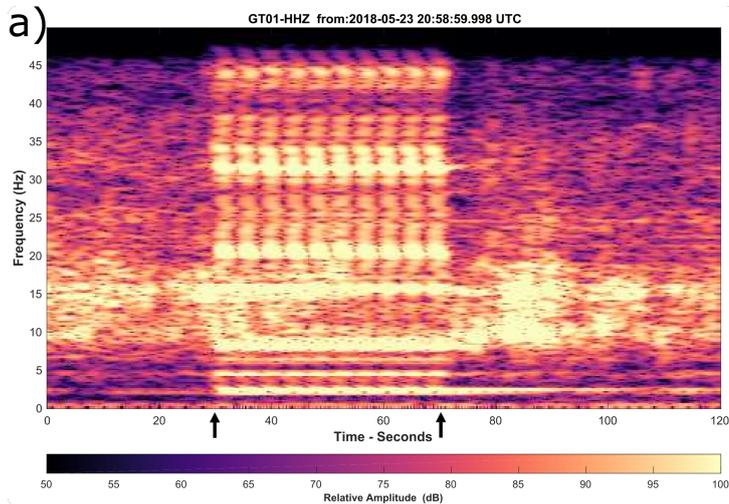


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Figure 3: 24 hrs of continuous seismic data recorded on three channels (HHE, HHN, HHZ) at the seismic station GT01, which is housed in the bell tower of the Wills Memorial Building. The orange box on HHE (top) trace highlights the bell chimes at 10 PM (9 PM UTC). The red box shows the much larger bell ringing for the Charter Day commemoration on 23 May 2018. Both highlighted signals are explored further in Fig. 4. The numbers in the upper right corner of each trace indicate the absolute maximum amplitude of that trace in counts.

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015 Figure 4: Zoomed-in spectrograms of the signals highlighted in Fig. 3. Plot a) shows the 10 PM (9 PM UTC) chiming of Great George in which each peal is visible particularly in the 15-25 Hz range. Plot b) shows a spectrogram of the Charter Day chimes; note that the time scales are different and the colour range on plot b) is larger than in plot a) to prevent colour saturation. Arrows indicate the start and end of the bell-ringing interval.

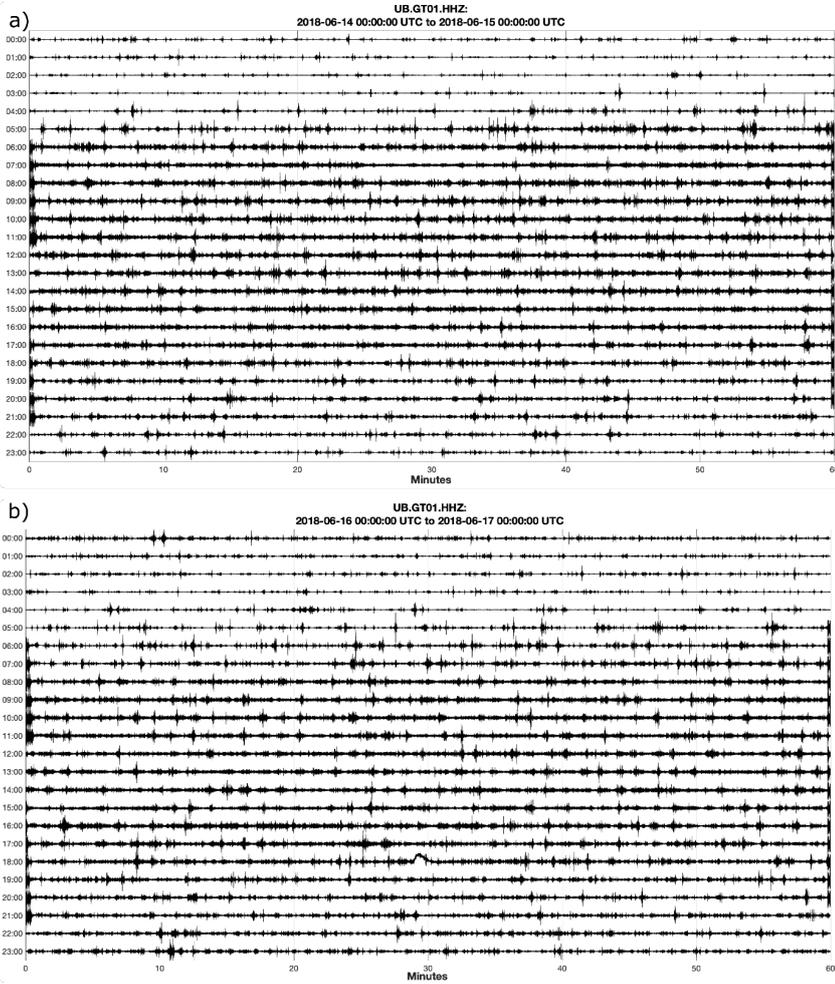
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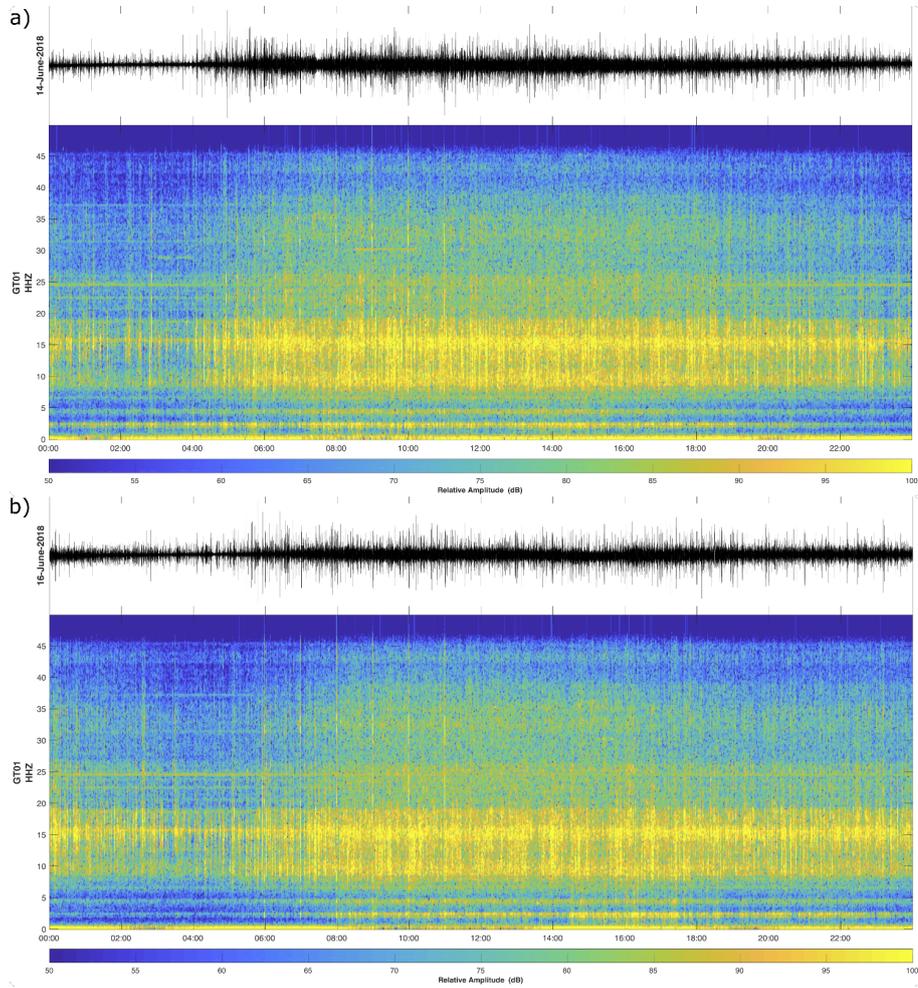
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025 Figure 5: Helicorder recordings showing seismic signals (a) during a typical weekday near the WMB tower and (b) during a Saturday evening near the tower. During the week, while never fully quiet, activity tends to wane at night around 10 PM in contrast to a weekend night when activity is heightened until about 3 AM.

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Figure 6: Spectrograms of the time-domain data shown in Fig. 5. The spectrogram is displayed in the bottom portion of plots: a) a weekday, and b) a day on the weekend. The top portion of each plot condenses the 24hrs of waveform data shown as a helicorder record in Fig. 5 into a single trace. The spectrograms show that there is strong energy in the 10-20 Hz frequency band throughout the day; this energy is almost continuous on the weekends (Plot b) but wanes slightly overnight on a weekday (Plot a).

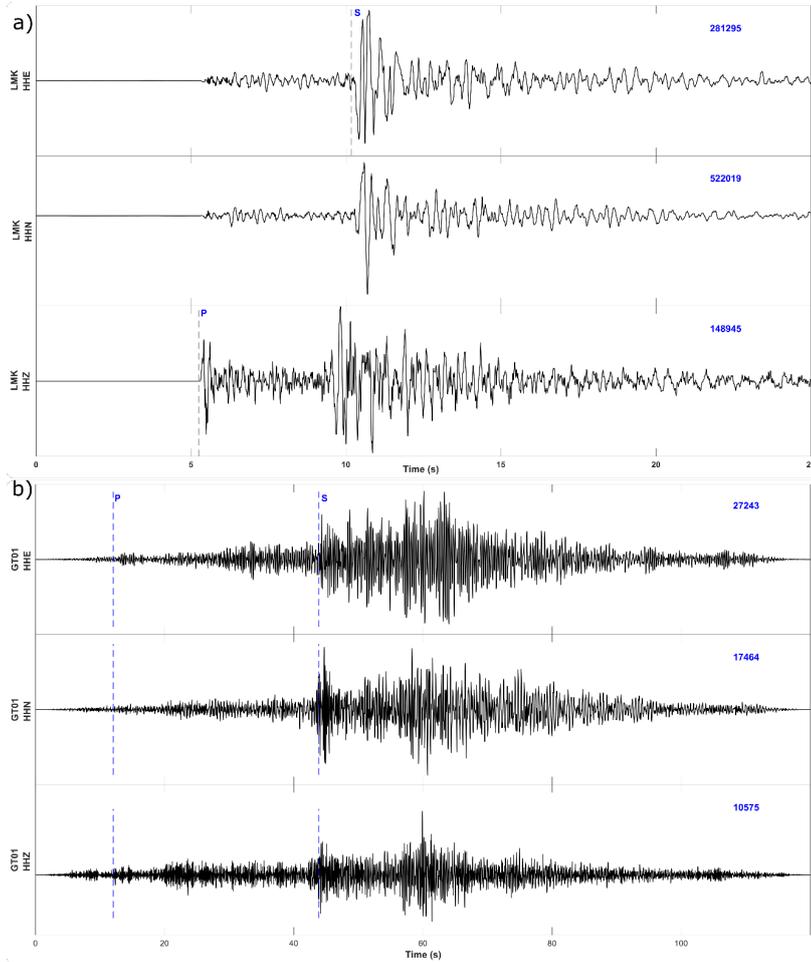
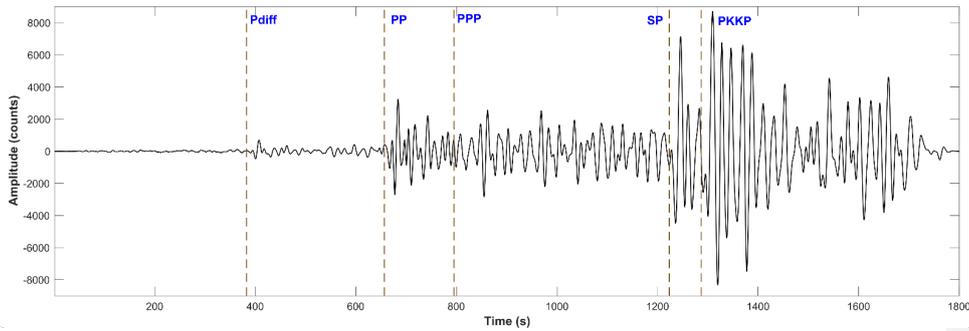


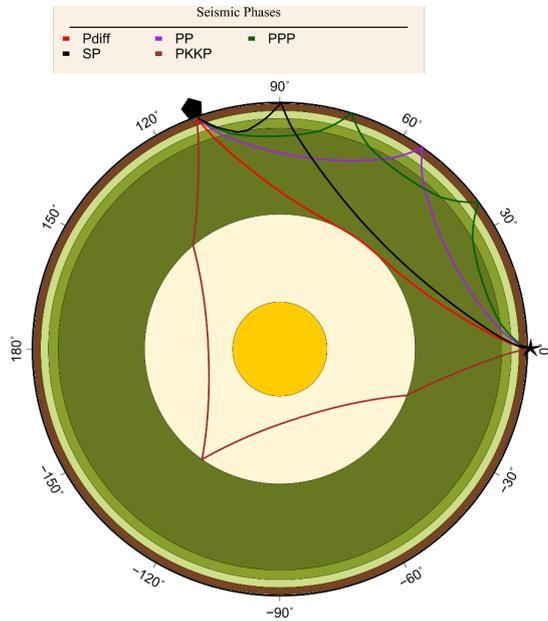
Figure 7: Lincolnshire earthquake (a) as recorded by station LMK (~5 km from the source), and (b) the later arriving signal at station GT01 in the WMB tower (~300 km from the source). The HHZ traces show the vertical components of ground motion and the HHE and HHN traces show the horizontal components, which are oriented E-W and N-S, respectively. Note the difference

040 between signal duration on both seismometers as well as the difference in peak amplitude given by the numbers in blue in the top right corner of each trace. The estimated arrivals of the P and S waves are indicated on both plots. Note that the zero time in each case is arbitrary and the time scale is different for the two seismometers.

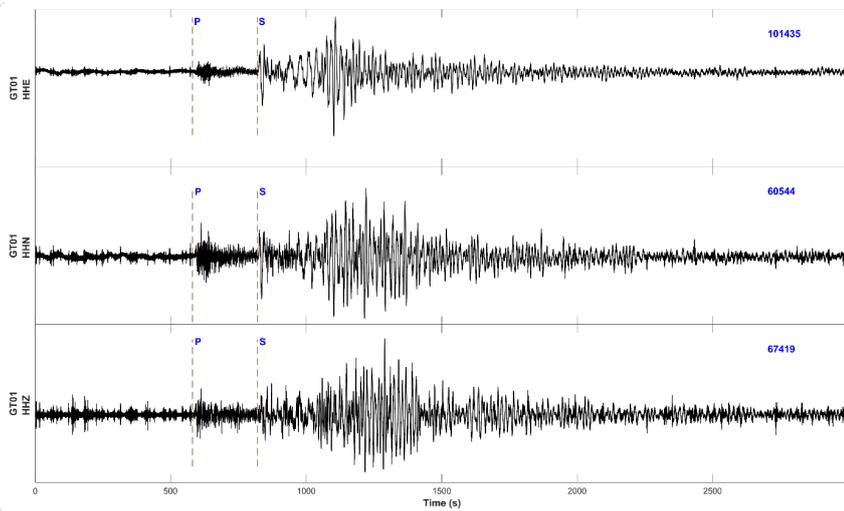
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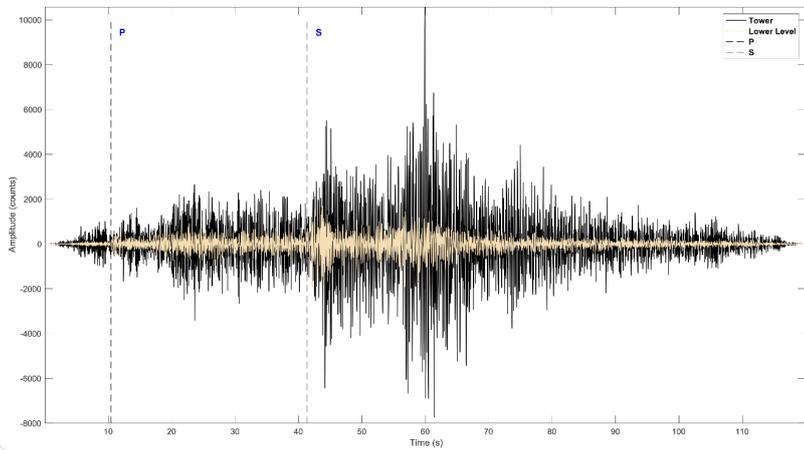
045 Figure 8: Filtered seismic waveform showing some of the seismic phases visible from the 28 September 2018 Palu, Indonesia earthquake. The vertical-component waveform is bandpass filtered between 0.01 and 0.1 Hz to isolate the signals of interest. The earthquake occurred at a depth of 20 km and was ~12,200 km from the recording station (GT01) in the Wills Memorial Building (source USGS (2018)).



1050 Figure 9: Plot showing some of the ray paths that seismic waves travelled from the source in Indonesia to the seismic station set up in the WMB tower. The star shows the earthquake epicenter while the pentagon denotes the station location. The inner core is shown in yellow, the outer core in beige, the mantle in green and brown in the image. The thin crust on which we live is the black outer layer, which is barely visible on the image. The arrivals of these phases are marked on the seismogram in Fig. 8.

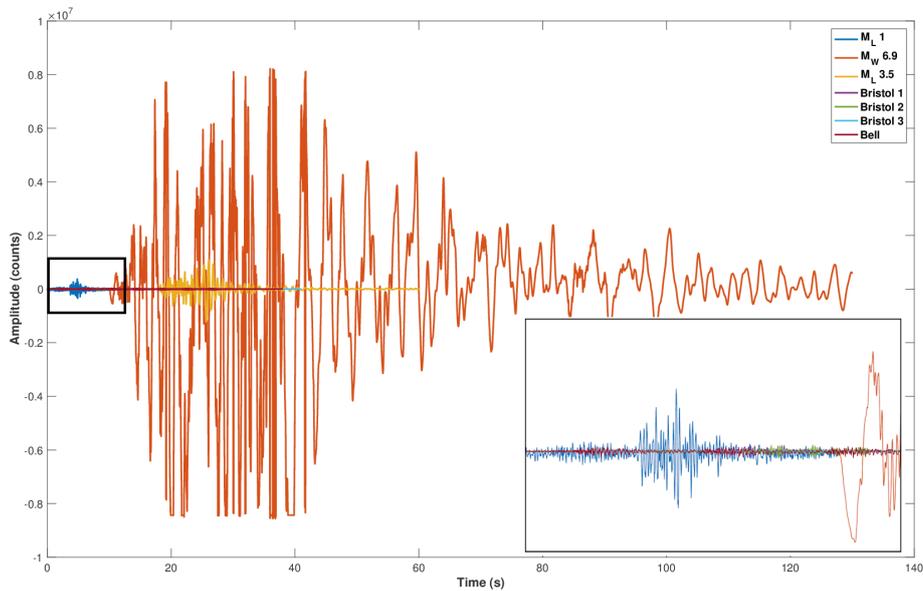


055 Figure 10: Seismic recording of the magnitude 6.8 earthquake that occurred 44 km SW of Mouzaki, Greece on 25 October 2018. The earthquake occurred at a depth of 14 km and was ~2,400 km from the recording station (GT01) in the Wills Memorial Building. The HHZ trace shows the vertical component of ground motion and the HHE and HHN traces show the two horizontal components, which are oriented E-W and N-S, respectively. P- and S-wave arrivals are indicated; the stronger lower-frequency energy that arrives after 1000s shows the arrival of the surface waves.



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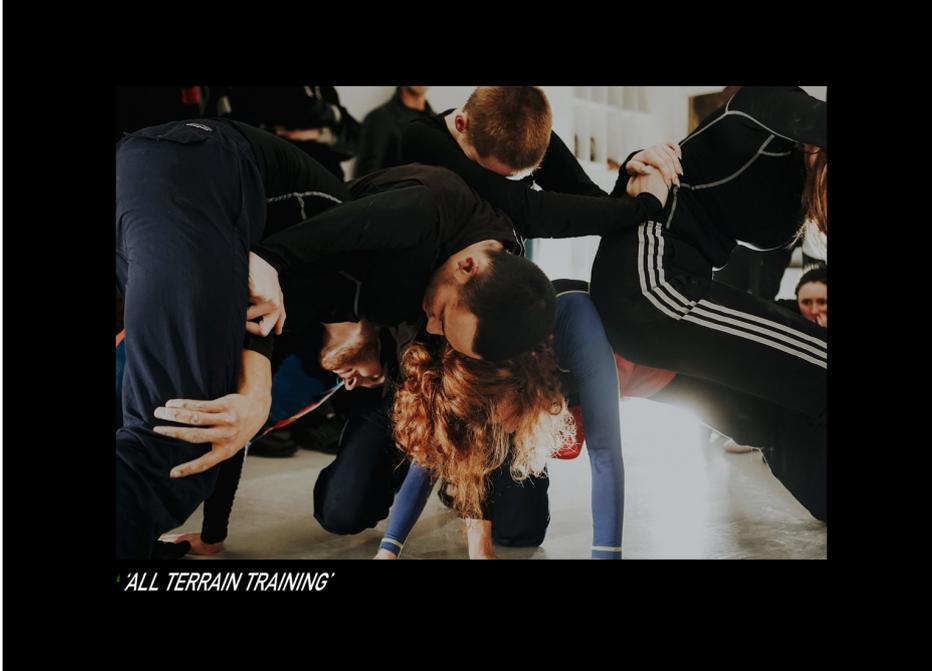
Figure 11: Seismic signals from the Lincolnshire earthquake recorded on one of the seismometers on the first floor of the WMB (beige) overprinted on a waveform of the same event recorded on station GT01 (black) in the WMB tower. The signal from the tower is more than double the amplitude of that recorded on the first floor of the building. Both traces were bandpassed filtered between 2 and 10 Hz.



1065 Figure 12: Comparison plot of different seismic signals from various sources recorded on stations in Hawaii (signals labeled M_L ,
 and M_w) and on GT01 in the WMB (signals labelled Bristol or Bell). Lower right inset shows a zoomed-in view of the same signals
 highlighted by the black rectangle in the main figure. From the inset image it can be seen that the background noise and the bell-
 ringing (green and magenta signals, respectively) recorded in the WMB tower fits neatly into the signal of a local magnitude 1 event
 1070 (dark blue) recorded on a station 1 km from the earthquake source in Hawaii. Given that magnitude 1 events are seldom felt, the
 inset makes it clear why the background activity around the tower goes largely unnoticed.

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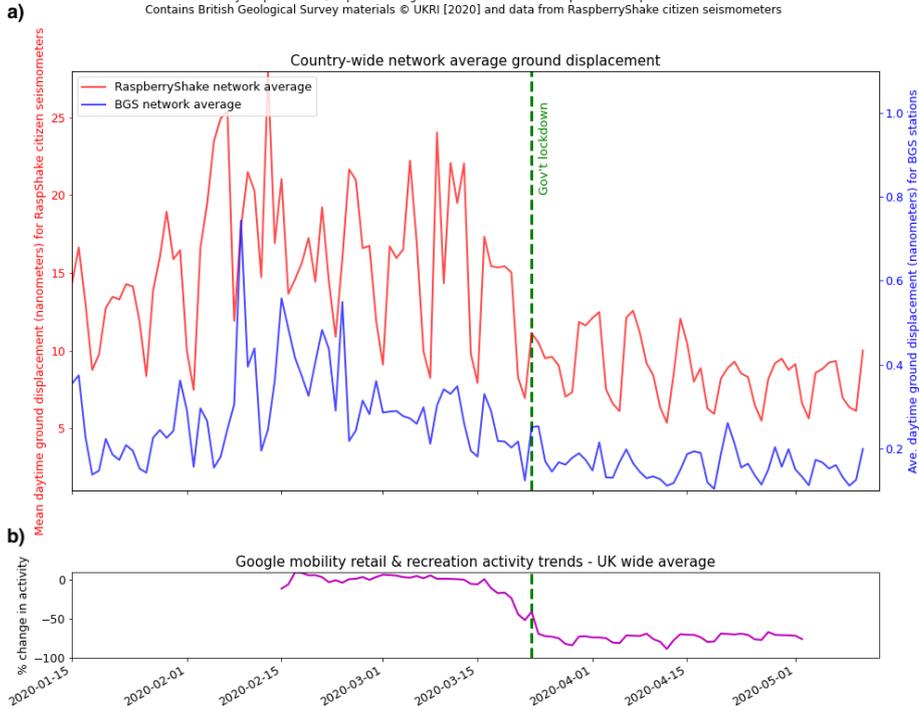
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1075 Figure 13: Artists perform a durational dance piece entitled All Terrain Training choreographed to sonified seismic data captured in the Wills Memorial Building tower that was amplified and live mixed during the event. The choreographed movements depict the collision, shearing and spreading of the tectonic plates that produced the earthquakes to which the piece was performed. Photo credit: Rocio Chacon

Seismic response in the UK to COVID-19 lockdown
2020-05-12 : 50 days since lockdown

Created by Stephen Hicks, Imperial College London. Noise levels computed at frequencies of 5-15Hz.
Contains British Geological Survey materials © UKRI [2020] and data from RaspberryShake citizen seismometers



085 **Figure 15:** a) Plot of average seismic noise recorded in the UK by the British Geological Survey (BGS) seismic network (blue) and the Raspberry Shake (RS) network (red) shows a marked decrease in seismic noise levels on both networks since the Covid-19 lockdown began on 23 March, 2020. This plot shows a decrease in average noise level of ~0.6 nanometres and ~15 nanometres on the BGS and RS network respectively between the peak noise levels in early February and the government lockdown in late March. b) The Google mobility data also depict a similar decrease in activity in the UK associated with retail and recreation activity trends post-lockdown. This plot shows that UK recreation and retail activity dropped by ~80 percent post-lockdown. Figure created by Dr. Stephen Hicks of Imperial College, London.

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