Tomographic Being

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To live on this planet is to be at once empowered and threatened by two monstrous sources of energy. From one direction arrive waves of electromagnetic energy generated by nuclear fusion within the nearest star, an irradiance so intense that it would be biologically lethal were it not for the shielding effect of Earth's magnetic field. From the other direction comes the seething heat left over from the accretion of the planet and fueled by decaying radioactive elements, thermal energy that flows upward and outward – not in waves but through mass movement of viscous rock.

What receives incoming solar radiation and impedes the escape of heat from the inner Earth is a shell composed of interlocking slabs of cold, hard rock. This lithic lid is global in extent but stretched so thin as to amount to only about 1% of the planet's mass. Along with the life that animates it, what is exceptional about this crust – at least in our own solar system – is its degree of mobility. Propelled by great churning currents in the mantle layer below and by the sinking of its own fragments, the plates composing this rocky platform inch along, colliding, sheering and folding to form the richly variegated surface upon which biological life dwells.

While the dynamism and variety of the outermost Earth has nudged life in new directions, eruptions of molten minerals from the planetary depths serve as a feedstock of the raw materials on which living things depend. But there is something else, just as remarkable, that the juddering motion of the Earth's crust has made possible. In recent decades, for the first time in the planet's history, one of the organisms that inhabits the outer Earth has hit upon a way of turning the grinding and clashing of the lithic slabs it rafts upon into a window to the interior of the planet.

Our own species shares many capabilities with other motile, warm-blooded, land-based lifeforms. Indirectly, solar radiation fuels our metabolism while sense organs and a central processing unit clustered at one end of our body utilize a spectrum of electromagnetic waves to help us navigate through a dynamic elemental world. In other ways, however, we are more unique. By manipulating fire, humans have extended their otherwise diurnal, surficial niche far into the Earth's crust, reaching depths rivalled only by microorganisms adapted over billions of years to heat, pressure and darkness. In the process we have enhanced our bodily senses and mechanical functions in ways that allow us to probe even further – well beyond the conditions that our bodies can tolerate. But the ability some of us have recently acquired to apprehend what is happening in the Earth's subcrustal interior requires other capacities, quite different from those we have developed to explore our planet's uppermost layers.

Without augmentation, there is nothing that the human sensorium can achieve which isn't bettered by other creatures. That applies especially to our perception of vibrations. Numerous accounts from many cultures tell of animals who anticipate earthquakes and move to safer ground. While some western researchers discount such evidence as anecdotal, others are willing to countenance the ability of certain animals to register low frequency pre-quake vibrations or the shifting electromagnetic waves that cause air ionization and water oxidation. On shorter timescales, there is evidence that certain animals can sense P waves of an earthquake – the 'primary' compressional waves that move through solids, liquids and gases – which tend to arrive seconds before the slower-moving, 'secondary' or 'shear' S waves that can only travel through solids. All of which makes a certain sense, as many living things communicate with and through vibration.

The earliest known human instrument to register seismic activity was invented by a second century Chinese astronomer. This 'seismometer' used a pendulum to indicate the direction of earthquakes, a basic principle redeployed in a succession of experimental tremor detecting devices constructed in Western Asian and Europe from the 13th century onwards. Still relying on a pendulum system, the first serviceable seismographs – instruments that automatically transcribe quaking ground into graphic representations –

were introduced in the 1870s and 80s, first by an Italian researcher and subsequently by a British team working in Japan. Contemporary successors of these devices use electronic sensors, amplifiers and recording mechanisms. Most are broadband, meaning that they cover a wide range of frequencies – waves with different cycles or repetitions per unit of time – which can include motions anywhere between 500 Hertz (1/500 or 0.002 seconds per cycle) and 0.00118 Hertz (1/0.00118 or 850 seconds per cycle). So too has coverage been extended along more familiar scales, as individual earthquake monitoring operations have meshed over time into networks of standardized seismic stations.

The main cause of earthquakes is the build-up of pressure through tectonic plate movement followed by sudden release of energy as stuck plates eventually slip or slide past each other – sending waves rippling through the solid Earth. As they radiate outward from their epicentre, these seismic waves resonate at wavelengths ranging from a few meters to thousands of kilometers: reverberations that, in the words of science writer Maya Wei-Haas, ring the Earth 'like a bell'. It is the damage wrought primarily by shear waves on human-built structures and the risk of tsunamis generated by seafloor tremors that have prompted installation of early warning systems and the as-yet unfulfilled quest for accurate earthquake prediction. But the same billowing energy waves that unleash destruction can also tell a story about the rock fabrics they have passed through. For like any waves, the pulses generated by seismic events reflect and refract as they traverse different kinds of matter. Because seismic waves move not only through the crust but proceed right through the planetary body, tracking these deflections can be used as a way of identifying variations in the composition, density and temperature of the Earth's interior.

The breakthrough with this technique came in 1909, when Croatian geophysicist Andrija Mohorovičić used seismographic records of a recent quake in Zagreb to deduce that the Earth is composed of several layers encircling a core and to establish that a significant discontinuity separated the planet's crust and mantle. By the 1970s and 80s, Japanese American seismologist Keiiti Aki and fellow researchers were using increasingly powerful computation systems to assemble data from seismometers into 3D images of the Earth's interior. The term that came be used for this imaging process – tomography, from the Greek *tomos:* slice or section – was borrowed from the field of medicine where X-rays, ultrasound and other waves had been used to penetrate living human bodies since the 1930s.

Whereas medical computed tomography or CT scans build up a picture of internal features of organic bodies based upon attenuation – loss of image quality when waves are impeded by some kind of compositional inconsistency – seismic tomography has relied upon the timing discrepancy of waves passing through the heterogenous planetary body as recorded by geographically distributed seismic monitoring stations. And while medical tomography involves human agents sending out the waves, seismic tomographers must await upheaval of the Earth itself as a wave source – though underground detonation of nuclear weapons has also provided shudders of sufficient magnitude to register on seismometers.

The term 'whole Earth' is closely associated with photographs of our planet taken from space taken by astronauts in the early 1970s. The achievements of seismic tomography, however, remind us how misleading that sense of 'wholeness' has been. Enthrallment with the planet's sunlit and life-infused surface has restricted imaginaries of nature, Earth, or the globe to a slender envelop: a reduction that is reinforced every time commentators invoke the end of nature or the ubiquity of the human planetary footprint. But the beauty of waves is that they come in many forms, some which play upon surfaces and others that press on through the masses we may too easily have assumed were impenetrable. By relentlessly tracking the latter – pursuing the rhythmical offspring of earthquakes through variably solid, viscous or molten rock – seismic tomographers have opened the inner Earth to scrutiny and intrigue. Tremor by tremor, they have begun to convert the planetary interior from an unfathomable volume or yawning void into a place. Or perhaps we might better view the field of seismic tomography as the grafting of an empirical supplement onto a much older set of cultural imaginings of the underworlds of everyday existence.

Today's accelerating technologically enabled encounter with the inner Earth may eventually incite its own mythos, but for now the advancing research front seems to be outrunning aesthetic and critical imaginations. Early experiments in seismic tomography entailed comparisons between arrays of 10 to 20 stations, current data sets are derived from hundreds or thousands of seismic sensors, and one recent project integrated recordings from 6 million seismic waveforms triggered by 2366 earthquakes. We should not forget, however, that for economic and geopolitical as well as topographical reasons the reach of global networks remains profoundly uneven. While attention zooms in on mantle activity beneath humankind's putative homeland in and around the East African Rift, for example, seismic monitoring is patchy over much of the African continent.

Novel twists on tomography, new data sharing protocols and escalating information processing power promise improved coverage. Seismic ambient noise – the background babble of weather events, ocean swells, tiny 'microseisms' and other small wave sources – was once treated as an interference in the field of more formidable convulsions. Aided by massive computational capacities, these continuous rumblings are now being redeemed as an extensive complementary data source for discrete events. Meanwhile, fibre optic cables are being repurposed as stretched out sensor arrays for shallower seismic events, while programs are available that turn smartphones into tremor detecting devices with capacity to feed millions of individual readings into seismic arrays and to disseminate equally expansive earthquake early warnings. As alert systems, apps like MyShake work on the basic principle that the speed of seismic waves – somewhere between 2000 and 10,500 meters per second – is considerably slower than the light speed – some 300 million meters per second -– of radio waves used by mobile phones.

Building on other innovations, full-waveform inversion can now model the frequency, velocity and amplitude – how much the ground moves up and down – of seismic waves, providing far richer detail than imaging based on travel time alone. As geophysicist Barbara Romanowicz extols, this technique 'makes it possible to exploit the information contained in every wiggle of a seismogram, produced by all the different seismic waves that bounce and scatter inside the Earth'. Practical applications of the fast-evolving tomographic toolkit are numerous, some hopeful, others giving cause for concern. They include improved understanding of volcanic and seismic hazards, below ground imaging of archeological sites, carbon storage monitoring, and oil and gas recovery.

Delving deeper into the Earth's interior the instrumental value is less clear though the level of wonderment may amplify. Seismic tomography is now mapping jagged 'mountains' higher than the Himalayas that march across the upper-lower mantle boundary some 650 kilometers beneath the Earth's surface, while full-waveform inversion models are helping piece together ancient processes of crustal formation such as the vulcanism that shaped the western Arabian Peninsula tens of millions of years ago. In the still bigger picture, such data contributes to what researchers describe as on ongoing revolution in the Earth sciences over the preceding decade and a half: developments that have fused data about surface and inner Earth processes into reconstructions covering the last billion years of planetary formation. In the words of geophysicist Sabine Zahirovic and his colleagues:

> These time evolving 4D Earth models have … provided insights on the evolution of the plate-mantle system over supercontinent cycles, as well as shed important insights into the role of the churning planetary interior in vertical motion of tectonic plates and the continents they carry.

This vast, upheaving canvas reminds us that humans have always been 'shockwave riders' on a planetary surface pitched into motion by immense forces from below and beyond. Though we may have only recently joined the Earth's most acute seismic-sensing organisms, the emergent ability of our species to attune to the music of the planetary body marks a historical threshold. It could also be construed as a turning point for the Earth itself, for never before has the planet's outer envelope been enrolled into such continuous and information-rich communication with the seething mass of its interior. A radical reconfiguration of the human sensorium, seismic tomography could also be regarded as an augmentation of the Earth's own self-sensing capacities.