From tools to technosphere

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The *Val d'Adige*, the upper valley of the Adige river, bisects the autonomous region of Trentino-Alto Adige in Northern Italy, and also divides the Dolomite mountains proper in the East of the region from the Brenta group of Southern Limestone Alps in the West. Archaeological digs have revealed many signs of human occupation of the area from the period between the last glacial maximum and the adoption of agriculture. When Mesolithic peoples were enjoying the bounty of the *Alto Adige*, they were inhabiting a region of hard dolomitic limestone that formed under the Tethys Ocean 200 million years ago but was then uplifted by the lithospheric processes that formed the Alps about 65 million years ago. The valley itself had then been carved into its distinctive flat-bottomed shape by the cryosphere – by the glaciers of the Pleistocene epoch. It had then been further shaped by the hydrospheric erosion and deposition processes in the Holocene, and filled with rich ecosystems as plant, animal and fungi species spread from 'refugia' to reoccupy the land exposed by the retreating glaciers. On the Eastern side of the valley, tributaries coming down from the Dolomites had fed in rich alluvial deposits, creating fertile areas that were good for hunting red deer, ibex, chamois and birds. The flat valley bottom itself was at that time full of marshes, lakes and braided river courses, rich in trout, pike, beaver and otter. On the Western, Brenta side, steeper and less fertile but catching more of the available sunlight, were a few natural rock shelters that provided good locations for the local population of humans to process carcasses and make tools (Clark 1999). In one of these locations, known as the Pradestel rock shelter, bone and antler artefacts from this period include bilateral harpoon points with straight barbs made from red deer antler, pointed tools such as awls made from bone using flint cutting tools and used in basket making, bevel-ended tools made from antler used for processes such as scraping hide, and objects related to manufacturing operations made from antler such as hammers and chisels (Cristiani 2009).

In these Mesolithic remains there are little signs of the pottery and ground stone tools that would become characteristic of the Neolithic, let alone the polished stone axes that would enable large-scale forest clearances, or the timber-framed 'long houses' in which settled farming communities were to live. And these is nothing particularly special about the artefacts at Pradestel, other than that they happened to be preserved, and then found and analysed by contemporary archaeologists. Nevertheless, they give us a good sense of how the Mesolithic peoples of Europe had adapted and developed their hunter-gatherer lifestyle, forged in Pleistocene glaciations, to the warmer, more fertile conditions of the Holocene, not least through the development of a wide range of new, specialised tools.

However, impressive as these tools are when compared with the earlier general-purpose stone tools of the Palaeolithic, it would have seemed implausible to imagine that out of objects such as these a whole new subsystem of the Earth could come into being, a distinct 'sphere' comparable in significance to the lithosphere, hydrosphere, cryosphere and biosphere that had been such powerful actors in the creation and shaping of the valley up till then. But such is the claim of writers such as Carsten Herrmann-Pillath (2013) and Peter Haff (2014b), who independently suggested that the Earth is developing a new major subsystem, the 'technosphere'. For Haff and Herrmann-Pillath, the technosphere is comprised of all interconnected technological systems and the entities (including human beings) that are necessary for their operation and survival, and is exhibiting its own endogenous dynamic, above and beyond the intentions of the humans that are involved with it. Surely, compared with the ancient and powerful spheres that shaped the Alto Adige, a handful of artefacts wielded by a small population of hominins are too weak and too weakly coherent a form of matter to engender a new major active subsystem of the Earth?

But if we were to carry out a comparable exercise with the precursor-entities of the biosphere in the Archean aeon of the early Earth, we might have come to a similar conclusion. Imagine a group of individual, free-living microorganisms living about four billion years ago in a hydrothermal vent or volcanic pool, perhaps gaining their metabolic energy from volcanic heat and the oxidation of sulphides, slowly exhausting the nutrients around them. These entities would also look like implausible candidates for the progenitors of a new major subsystem or 'sphere' of the Earth. Yet we know that two billion years later living things were establishing a global ecosystem that would come to shape the operation of the other Earth systems in hugely consequential ways (Lenton and Watson 2011). So maybe we should not dismiss too readily the idea that human artefacts like those discovered in Pradestel could trigger an event of planetary scale. But what does it take to establish a sphere of the Earth from such unpromising, heterogeneous materials?

How to make a sphere

All major subsystems or active 'spheres' of the Earth can be understood as thermodynamic, autopoietic entities. They are *thermodynamic* in that they are far-from equilibrium systems that follow the thermodynamic laws governing the availability of energy to do work (Kleidon 2016). The famous second law states that over time closed systems will approach thermodynamic equilibrium, a state in which entropy or disorder is at a maximum and available energy at a minimum. However, planetary subsystems are dissipative systems – that is, open systems that exchange energy and/or matter with their environment, and do so in a way that results in them adopting a stable dynamic state far from equilibrium, thus maintaining their amounts of internal order and free energy. Such systems also follow the Maximum Entropy Production Principle (MEPP), developed by Jaynes and Dewar, which says that will over time they will tend to adopt those states (from the range of states available to them) that maximise the production of the total combined entropy or disorder in the system and its environment – but in so doing will themselves become even more ordered (Dewar 2005; Prigogine and Glansdorff 1971). Thus river valleys, like that of the Adige and its tributaries, organise themselves into fractal complex fractal networks that drain in optimal ways (Rodríguez-Iturbe and Rinaldo 1997).

But planetary spheres are also *autopoietic* ('self-making') entities – that is, they continuously regenerate the network of relations that produce them, specify their own boundaries in the processes of self-production, and are operationally closed, or self-referential, which means that they do not have 'inputs' or 'outputs', since exogenous events are 'experienced' by the system in the terms of its own operation (Maturana and Varela 1980). In fact it would be more precise to say that, over time, planets can become able to establish spheres that are autopoietically more complex. The emergence of autopoiesis is usually seen as a once-and-for-all change; a system is seen as either allopoietic (where the product and that which produces it are separate entities) or autopoietic (self-making), with no gradations between. However, I want to argue that the operational closure and self-reference that is seen as a distinguishing feature of biological and social systems can also be seen as prefigured in nonbiological planetary systems. This insight can help us place planetary spheres in the deep time of planetary evolution.

In order for a planetary sphere to establish itself, it needs at least one gradient and one gratuity. By a 'gradient' I mean a difference in the magnitude of a property such as temperature, density, height (and thus gravitational potential energy) or chemical concentration at different points in space. Such a gradient can enable a sphere to come into being, by helping its constituent parts to gather themselves. It can also help to power its motion, especially if it is a constantly renewed gradient like that provided by solar radiation. It can also help the sphere to organise and complexify itself over time. By a 'gratuity' I mean a form of arbitrariness that can sometimes open up in a dynamic process, thereby creating a new space of freedom that can be explored and occupied by the system. An example of such a gratuity is the arbitrary relation between chemical and physical function opened up by the genetic code, that created the vast possibility space to be explored by biological evolution (Monod 1972). We can roughly distinguish two roles of gratuities in the emergence and development of planetary subsystems. The first is the emergence of an operational boundary, that defines inside and outside, through a specific mode of existence or set of operational codes. The second role is that of facilitating the progressive establishment of a space of possibility to explore and inhabit – and one that is capable of establishing a self-reinforcing dynamic to allow the new system to persist and grow.

Some spheres – like the lithosphere, hydrosphere and atmosphere – are likely to establish themselves widely on many planets, and early on in their development. This is because here, thermodynamic processes dominate, and the first kind of gratuity is generated directly by the operation of these processes. These 'early-planetary spheres' emerge through what Terrence Deacon (2006) calls 'first-order emergence', in which global properties are all produced bottom-up from the interaction of individual parts as they seek thermodynamic equilibrium and thus destroy the gradient that created them. Such spheres are produced by the very gravitational processes through which planets form, as the diverse chemical elements making up the nascent planetary body find their 'hydrostatic' level in the forming spherical body of the planet, and adopt different phase states (solid, liquid, gas, mineral type) according to the ambient temperature and pressure of that part of the planet. The relative gratuity, spatial boundedness and operational closure of these spheres are emergent properties of the different physics of solids, liquid and gases, and the way that thermodynamics and chemical affinity limit fluxes across the surfaces. Such spheres become relatively closed in a material sense, but they are not self-referential, properly autopoietic – operationally they are unable to decomplexify their causal relations with their environment, so that causal influences such as heat and kinetic energy are simply passed between them.

But planets thus differentiated, and then kept far from equilibrium by incoming solar radiation and leaking heat from the inner core – and particularly those that are able to generate and keep fluid spheres – may become what Frank et al. (2017) call Class II planets. Such planets, driven by the continually renewed applied gradient, exhibit geochemical cycling, in which the cycles perform thermodynamic work on each other, pushing each other further from equilibrium and maintaining the gradients that power them (Kleidon 2016), so that both the spheres themselves, and the interactions between them, become more complex. This is Deacon's 'second-order emergence', in which a more complex, 'recurrent' causal architecture means that large-scale structures serve to shape and amplify lower-level processes.

For example, the Earth's hydrosphere is not simply a continuous, hydrostatically equilibrated stratum of liquid on the Earth, but an active system that is far from gravitational, thermal and chemical equilibrium. This is the case in the Val d'Adige, where the convecting mantle has driven up the Alps, creating the altitude gradient between the source and mouth of the Adige, and where the atmospheric motion driven by the temperature gradient between different parts of the spherical Earth produces the precipitation that keeps the Adige and its tributaries flowing. The Earth's hydrosphere also exhibits self-organised criticality (Bak 1996), and is relatively 'self-referential' in that it has its own distinctive elements and operations which exhibit a degree of autopoiesis. Its internal operations are thus *perturbed*, rather than simply causally affected, by its lithospheric and atmospheric environment, so that it is thus able to become more complex than its environment. Through processes such as erosion, solution and deposition it organises its interactions with the lithosphere, creating a more ordered environment for the flowing water (Rinaldo et al. 1993).

However, given time, planets may also generate one or more *new kinds* of planetary subsystems that are more contingent in their form and that achieve relative autonomy in a more active way. Such 'late-planetary spheres' exhibit the kind of self-making that the concept of autopoiesis was initially meant to specify, the ontological mode of existence exhibited by living things. This is Deacon's 'third-order emergence', fully autopoietic, in which memory systems produce more complex causal loops, which allow new forms of structure and behaviour to be maintained and reproduced across time and space. This autopoiesis is crucial to the binding together of the Earth's biosphere, made up of diverse kinds of materials and phase states, which can disperse and intermingle with other spheres without the biosphere losing its own kind of closedness. But this strongly autopoietic, third-order emergence is also characteristic of the technosphere, to which we must now turn.

From tools to technosphere

Applying the concept of autopoiesis to the technosphere might seem perverse. The discussion of autopoiesis usually uses machines as an example to define autopoiesis *against*: human-made machines are seen as allopoietic, since they do not create their own components or needs, or define their boundaries or operations (Maturana and Varela 1980: 79; see also Luhmann 2013: 66-8). This may well be true of individual tools and machines – however, when we look at the technosphere *as a whole system*, this looks much more like a candidate for being autopoietic.

The technosphere as we are beginning to understand it shares many features with the biosphere; in the case of the biosphere and the technosphere, where their constituent entities are and what they are made of seem to be less important than the processes of autopoiesis and operational closure that bind them into the system. The Earth's biosphere and technosphere, I want to suggest, are examples of the kind of autopoietic planetary subsystems that, depending on conditions, can establish themselves in the later stages of planetary evolution. But how could the kinds of artefacts discovered in the Mesolithic strata of the Pradestel rock shelter start to open up such a subsystem? To answer this question, we would need to map the meshwork of gratuities that *created* the new sphere's relative autonomy, that *constituted* its possibility space of innovation and action, and that *conditions* its evolution and its future prospects. Here I can only sketch the outlines of this meshwork.

The first kind of gratuity needed for a planetary sphere is one that establishes a specific mode of existence: one that involves a set of operational codes that defines the inside and outside of the system, and thus inaugurates an operational boundary. Peter Haff (2014a) has identified the two key emergent rules determining the behaviour of the technosphere as the 'rule of performance' and the 'rule of provision', which in effect regulate the responsibilities of all individual entities caught up in the technosphere and the wider system respectively. But when it comes to individual technical artefacts and how they are able to establish a separate sphere, we can perhaps be more specific. Tools and machines lack an innate *telos*, incapable of orienting their activity to an inherent goal, and require goals to be imposed on them from outside (Mitcham 1990); this is at the same time their weakness and their strength, which makes them *available for use*. Technological objects operate largely with the binary code of 'work/'fail' (Reichel 2011), but this code itself also has two dimensions: 'working' and 'function' (Sigaut 1985: 437). *Working* is more 'internal' and concerns the way that a technology harnesses physical effects or principles, such as those involved in electric motors; *function* concerns the 'external' role that the tool or machine performs in a wider action sequence or social or technical system. Early human technologies, like those of other tool-using animals, largely served to extend the individual powers of the body as arranged across its various organs and limbs – arms, fists, fingers, eyes, ears (McLuhan 1964). The 'clades' or lineages of early technologies – spears, bowls, needles and so on – were determined by the bodily form of the animals that made and wielded them. Tools are in effect bodily organs, limbs or powers that have been externalised, so can be picked up by others – another crucial aspect of their constitutive gratuity, which also further subjects them to the 'work/fail' code.

Then, for a nascent sphere to grow and become more elaborate, it needs gratuities that will enable the progressive establishment of a space of possibility to explore and inhabit, and a self-reinforcing dynamic that will allow the new autopoietic dissipative system to persist and grow. In the case of the Earth's technosphere this has involved a specific set of technical innovations that have shaped its *de facto* composition. Mapping these gratuities properly would be a project in itself, and I can only gesture here in what I think are productive directions. Many of these gratuities have involved what are known as 'general purpose technologies' (Bresnahan and Trajtenberg 1995), which offered new interconvertibilities between motion, energy and (increasingly) information. For example, *mechanics* involves the use of devices such as levers, screws, chains and belts, cogs, sails and keels that turn the energy of motion in new directions; *hydroengineering* converts the gravitational potential energy of rain on high land into mechanical work; and the *steam engine* and other heat engines convert heat gradients into mechanical motion. The importance of key twentieth-century innovations has been largely grounded in their ability to further extend interconvertibility, for example *electricity*, convertible into motion, heat, light and so on (Smil 2006), and *digital technologies*, from weaving to computers, which can transpose information between potentially any substrate or process. Finally, other very different forms of gratuity have been crucial for the dynamism and spatial reach of the technosphere: forms of *general-purpose money* that can serve as a medium of exchange, store of value and means of deferring payment across potentially unlimited spheres of human activity (Hornborg 2016), and processes of *product standardisation* that have enabled the more rapid spread of artefacts and expanded their use value (Busch 2011).

The technosphere, constituted by this meshwork of gratuities, and powered by flows of matter and energy down gradients from source to sink (Garrett 2014), seems to be constituting itself as a networked global entity that is demonstrating further emergent dynamics at the global level. Techno-economic history has been lumpy, with transitions between different prime movers and spatial organisation (Perez 2002; Smil 2010); however, as the work of Andrew Jarvis and others shows, global primary energy use has stayed close to an exponential curve for at least a century and a half (Jarvis et al. 2015). Energy use has also exhibited long- and short-term waves which seem to be the result of the system searching for ways to stay on track; economies seem to be developing to keep energy use growing, rather than the other way round (Jarvis 2018). As the technosphere has grown, falling efficiency due to longer path lengths has also been compensated for by the innovation and diffusion of new technologies, dematerialisation, and increased end-use efficiencies, at rates which seem to be regulated by the overall system dynamics (Jarvis et al. 2015). The technosphere shows all the signs of having constituted itself as an autopoietic system that defines its own boundary and reproduces its own operational code.

Conclusion

When the people of the Mesolithic roamed the Alto Adige they were inhabiting an area that had been created and transformed by powerful Earth systems. But in more recent times, as the technosphere has slowly established itself on the Earth, the *Val d'Adige* has been shaped by very different processes, and has taken up new roles and functions. The river itself was canalised in the medieval period in order to liberate the valley floor for settlement and agriculture, especially viniculture. The Roman settlement of Tridentum, situated just a few kilometres southeast of the Pradestel rock shelter, has now become Trento, one of the wealthiest cities in Italy. The gradient provided by the uplift of the Alps is still important in the dynamics of the region: the flow of the river is still used for irrigation, and now for hydro-electric power. But the valley is now also connected to and shaped by more distant gradients.

A key gradient powering the technosphere is the chemical gradient between subterranean fossil fuel deposits and the Earth's surface. Powered largely by the chemical potential energy residing in this gradient, the technosphere is growing and interlinking in ways that follow patterns of optimal space-filling familiar, from other, non-human resource acquisition and distribution networks (Jarvis et al. 2015). Because of this, combined with the constraints provided by the dolomitic limestone mountains that surround it, the *Val d'Adige* has long been important as the main transport route between Italy and Austria. The Adige drainage basin is bounded on the north by the watershed that separates it from the Danube basin, and the Adige itself and its tributary the Eisack or Isarco both have their sources near important mountain passes on that watershed – the Reschen and Brenner passes respectively. In the mid-nineteenth century the Austro-Hungarian Empire, that then included Northeast Italy as far as Venice, decided for economic and geopolitical reasons that it needed faster and safer transport links with its territories south of the Alps, and built the 'Brenner railway', the first railway line to cross the Alps. Starting at Verona, this line goes north along the *Val d'Adige*, through Trento up to Bolzano, from where it follows the tributary the Eisack up to its source near the Brenner Pass, and onwards to Austria and Innsbruck. Today the A22 trunk road follows a similar route along the Adige and Eisack valleys, connecting Italy with Austria.

Like the appearance of the earliest forms of reproducing life, perhaps made up of a mixture of autocatalytic molecules bounded by lipid membranes, the appearance of the earliest human tools seems an extraordinary and low-probability achievement, given what we know about the laws governing material self-organisation. What seems perhaps even more extraordinary is the trajectory leading forward in time from these two moments of ontogenesis, whereby these two fragile and unpromising forms of organised matter each came to spawn a whole subsystem of the Earth. However, such is the nature of autopoiesis that it is the first two stories – the chains of causation leading *up* to the first manifestations of life and of human consciousness and technicity respectively – that continue to elude human comprehension. The stories leading *forward* from those two events in Earth history seem more amenable to systematic understanding. In the century and a half since Darwin's *Origin of Species* (1859) we have learnt much about the emergent dynamics of the biosphere; in the case of the technosphere – let alone the wider possibility space of late-planetary spheres of which these two probably represent only two of many possible examples – the work is only just beginning.

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