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Short communication

Human bioturbation, and the subterranean landscape of the Anthropocene

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ABSTRACT

Bioturbation by humans ('anthroturbation'), comprising phenomena ranging from surface landscaping to boreholes that penetrate deep into the crust, is a phenomenon without precedent in Earth history, being orders of magnitude greater in scale than any preceding non-human type of bioturbation. These human phenomena range from simple individual structures to complex networks that range to several kilometres depth (compared with animal burrows that range from centimetres to a few metres in depth), while the extraction of material from underground can lead to topographic subsidence or collapse, with concomitant modification of the landscape.

Geological transformations include selective removal of solid matter (e.g. solid hydrocarbons, metal ores), fluids (natural gas, liquid hydrocarbons, water), local replacement by other substances (solid waste, drilling mud), associated geochemical and mineralogical changes to redox conditions with perturbation of the water table and pH conditions and local shock-metamorphic envelopes with melt cores (in the case of underground nuclear tests). These transformations started in early/mid Holocene times, with the beginning of mining for flint and metals, but show notable inflections associated with the Industrial Revolution (ca 1800 CE) and with the 'Great Acceleration' at ~1950 CE, the latter date being associated with the large-scale extension of this phenomenon from sub-land surface to sub-sea floor settings.

Geometrically, these phenomena cross-cut earlier stratigraphy. Geologically, they can be regarded as a subsurface expression of the surface chronostratigraphic record of the Anthropocene. These subsurface phenomena have very considerable potential for long-term preservation.

Introduction

Human modification of the surface of the Earth is now extensive. Clear and obvious changes to the landscape, soils and biota are accompanied by pervasive and important changes to the atmosphere and oceans. These have led to the concept of the Anthropocene (Crutzen and Stoermer, 2000; Crutzen, 2002), which is now undergoing examination as a potential addition to the Geological Time Scale (Zalasiewicz et al., 2008; Williams et al., 2011; Waters et al., 2014). These changes are significant geologically, and have attracted wide interest because of the potential consequences, for human populations, of living in a world changed geologically by humans themselves.

Humans have also had an impact on the underlying rock structure of the Earth, for up to several kilometres below the planetary surface. Indirect effects of this activity, such as the carbon transfer from rock to atmosphere, are cumulatively of considerable importance. However, the extent and geological significance of subsurface crustal modifications are commonly neglected: out of sight, out of mind. It is a realm that ranges from difficult to impossible to gain access to or to experience directly.

However, any deep subsurface changes, being well beyond the reach of erosion, are permanent on any kind of human timescale, and of long duration even geologically. Hence, in imprinting signals on to the geological record, they are significant as regards the human impact on the geology of the Earth, and therefore as regards the stratigraphic characterization of the Anthropocene.

This phenomenon is not something that falls neatly into any chronostratigraphic classification, given that relationships here are cross-cutting, not superpositional, and they typically represent more or less in situ modification of older rocks, rather than the

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creation of new strata at the surface. The large-scale 'anthroturbation' resulting from mining and drilling has more in common with the geology of igneous intrusions than sedimentary strata, and may be separated vertically from the Anthropocene surface strata by several kilometres.

Here, we provide a general overview of subsurface anthropogenic change and discuss its significance in the context of characterizing a potential Anthropocene time interval.

The palaeontological context: comparisons with non-human bioturbation

Bioturbation may be regarded as a primary marker of Phanerozoic strata, of at least equal rank to body fossils in this respect. The appearance of animal burrows was used to define the base of the Cambrian, and hence of the Phanerozoic, at Green Point, Newfoundland (Brasier et al., 1994; Landing, 1994), their presence being regarded as a more reliable guide than are skeletal remains to the emergence of motile metazoans.

Subsequently, bioturbated strata became commonplace – indeed, the norm – in marine sediments and then, later in the Palaeozoic, bioturbation became common in both freshwater settings and (mainly via colonization by plants) on land surfaces. A single organism typically leaves only one record of its body in the form of a skeleton (with the exception of arthropods, that leave several moult stages), but can leave very many burrows, footprints or other traces. Because of this, trace fossils are more common in the stratigraphic record than are body fossils in most circumstances. Trace fossils are arguably the most pervasive and characteristic feature of Phanerozoic strata. Indeed, many marine deposits are so thoroughly bioturbated as to lose all primary stratification (e.g. Droser and Bottjer, 1986).

In human society, especially in the developed world, the same relationship holds true. A single technologically advanced (or, more precisely, technologically supported and enhanced) human with one preservable skeleton is 'responsible' for very many traces, including his or her 'share' of buildings inhabited, roads driven on, manufactured objects used (termed technofossils by Zalasiewicz et al., 2014), and materials extracted from the Earth's crust; in this context more traditional traces (footprints, excreta) are generally negligible (especially as the former are typically made on artificial hard surfaces, and the latter are generally recycled through sewage plants).

However, the depths and nature of human bioturbation relative to non-human bioturbation is so different that it represents (other than in the nature of their production) an entirely different phenomenon. Animal bioturbation in subaqueous settings typically affects the top few centimetres to tens of centimetres of substrate, not least because the boundary between oxygenated and anoxic sediment generally lies close to the sediment-water interface. The deepest burrowers include the mud shrimp *Callianassa*, reach down to some 2.5 m (Ziebis et al., 1996). Below subaerial surfaces, animal burrows are not very much deeper, the deepest burrowers typically cited being wolves and foxes, at up to four metres, though aestivating Nile crocodiles (*Crocodylus niloticus*) may reach up to 12 m depth (Voorhies, 1975). Prehistoric animals likely did not attain significantly greater depths; dinosaur burrows, for example, were long unrecorded, and the single example known (Varricchio et al., 2007) is not much more than 20 cm across and lies less than a metre below the palaeo-land surface.

Plant roots can penetrate depths an order of magnitude greater, especially in arid regions: up to 68 m for *Boscia truncata* in the Kalahari desert (Jennings, 1974). They can be preserved as rootlet traces, generally through diagenetic mineral precipitation or remnant carbon traces. Roots, though, typically infiltrate between sediment grains, limiting the amount of sediment displacement and hence disruption to the rock fabric.

At a microscopic level, too, there is a 'deep biosphere' composed of sparse, very slowly metabolizing microbial communities that can exist in pore spaces and rock fractures to depths of 1–2 km (e.g. Parkes et al., 1994). These may mediate diagenetic reactions where concentrations of nutrients allow larger populations (such as the 'souring' of oil reservoirs) but otherwise leave little trace in the rock fabric. Very rarely, these communities have been found to be accompanied by very deep-living nematode worms (Borgonie et al., 2011), but these seem not to affect the rock fabric, and we know of no reports of their fossil remains or any traces made by them.

The extensive, large-scale disruption of underground rock fabrics, to depths of >5 km, by a single biological species, thus represents a major geological innovation (cf. Williams et al., 2014). It has no analogue in the Earth's 4.6 billion year history, and possesses some sharply distinctive features: for instance, the structures produced reflect a wide variety of human behaviour effected through tools or more typically mechanized excavation, rather than through bodily activity. Hence, the term 'anthroturbation' (Price et al., 2011; see also Schaetzl and Anderson, 2005 for use in soil terminology) is fully justified, and we use this in subsequent description below.

Surface anthroturbation

This is extensive, and distantly analogous to surface traces left by non-human organisms. It includes surface excavations (including quarries) and constructions, and alterations to surface sedimentation and erosion patterns, in both urban and agricultural settings. Its nature and scale on land has been documented (e.g. Hooke, 2000; Hooke et al., 2012; Wilkinson, 2005; Price et al., 2011; Ford et al., 2014) and it extends into the marine realm via deep-sea trawling (e.g. Puig et al., 2012) and other submarine constructions. Here we simply note its common presence (Hooke et al. (2012) estimated that humans have modified >50% of the land surface) as our focus is on the subsurface phenomena that descend from this anthropogenically modified surface level.

Shallow anthroturbation

Shallow anthroturbation extends from metres to tens of metres below the surface, and includes all the complex subsurface machinery (sewerage, electricity and gas systems, underground metro systems, subways and tunnels) that lies beneath modern towns and cities. The extent of this dense array is approximately coincident with the extent of urban land surfaces (some 3% of land area: Global Rural Urban Mapping: http://sedac.ciesin.columbia.edu/data/collection/grump-v1; though see also Klein Goldewijk et al., 2010).

Shallow anthroturbation also includes shallow mines, water wells and boreholes, long-distance buried pipes for hydrocarbons, electricity and water and tile drains in agricultural land. The extensive exploitation of the subsurface environment, as symbolized by the first underground railway system in the world (in London in 1863) was chosen as a key moment in human transformation of the Earth, and suggested as a potential 'golden spike' candidate, by Williams et al. (2014). These buried systems, being beyond the immediate reach of erosion, have a much better chance of short- to medium-term preservation than do surface structures made by humans. Their long-term preservation depends on them being present on descending parts of the crust, such as on coastal plains or deltas.