

An Anthropocene Species of Trouble? Negative Synergies between Earth System Change and Geological Destratification

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When the Fan hits the Shit

On 9 February 2014, during one of the hottest and driest summers on record, embers from a nearby bushfire set alight exposed open-cut coal seams at the Hazelwood Mine in the Australian state of Victoria. Fires burned for 45 days, blanketing smoke and ash over surrounding towns in the La Trobe Valley and adding significantly to greenhouse gas emissions from the Hazelwood Power Station, already ranked as the OECD's least carbon-efficient power plant (Melody and Johnston, 2015). As the Hazelwood Mine Fire Inquiry reported, Victoria is one of the world's most bushfire-prone areas and faces increasing frequency of extreme fire weather. But the Inquiry failed to make reference to climate change or to the positive feedback between carbon emissions from coal-fired power generation and wildfire risk (Rickards, 2014).

We propose that the Hazelwood Mine Fire exemplifies a particular 'species of trouble' that is becoming more pronounced under Anthropocene conditions. It is already well understood that unbinding materials and energy from their lithic reservoirs impacts upon Earth systems, a dynamic that is especially well documented in the case of the connection between fossil fuel combustion and climate change but also pertains to perturbation of the phosphorus cycle and rising ocean acidification (Steffen et al., 2015). There is less systematic engagement, however, with the multiple ways in which subsequent Earth system change reacts back upon the social infrastructures of subsurface exploitation and the landscapes they produce. Surveying research on the climate change–mining interface, Phillips observes 'The potential and actual interactions between climate change and surface mining have been, until recently, poorly understood and even neglected' (2016: 96). This is shortfall that we suggest has much broader applicability.

Alongside its contributions to Earth system change, transformation of the Earth's surface by mineral and energy extraction is so extensive that it has been considered as an 'ancillary marker' for the start of the Anthropocene epoch (Cooper et al., 2018: 228). The amount of sediment currently added to the global flux by anthropogenic mineral extraction has been estimated at more than 24 times the volume of sediment transported by the world's major river systems (Cooper et al., 2018). Extraction-related geological mass transfer increased substantially during the Industrial Revolution and post-1950 Great Acceleration (Cooper et al., 2018; Zalasiewicz et al., 2014). In more patchy and localized ways, anthropogenic mineral extraction has been significantly impacting rock fabrics and sediment fluxes since the emergence of metal industries some 6000 years ago – and such disturbance may be considered a basic corollary of large-scale urban life. In turn, displaced geological materials resulting from extractive operations have always been subject to subsequent impingement by an Earth system in which 'variability abounds at nearly all spatial and temporal scales' (Steffen et al., 2004: 295). What is unprecedented, however, is not simply the current rate and cumulative impact of geological transfer, but its exposure to an Earth system undergoing fundamental shifts in its functioning and overall state – changes that may turn out to be abrupt, cascading and irreversible (Steffen et al., 2015; Steffen et al., 2018).

Our concern in this paper is the increasingly catastrophic interface between Earth system change and anthropogenic processes of extracting materials from the Earth's crust – or what we refer to as 'geological destratification'. While geological destratification is instrumental in triggering climate change and other kinds of Earth system change, these changes in turn perturb extractive infrastructures and landscapes, generating further impacts on Earth systems. If not always contributing directly to positive feedbacks as in the Hazelwood mine fire example, these second generation impacts nonetheless have ongoing degrading and destabilizing effects that we refer to as negative synergies (Homer-Dixon, 2006: 106-7). To put a spin on the vernacular, we might say that these are events in which the fan hits the shit.

We see this focus on negative synergies between Earth system change and the edifice of destratification as complementing Anthropocene geoscience's concern with the contemporary formation of novel lithic strata (Price et al., 2011; Edgeworth, 2018; Zalasiewicz et al., 2019: Ch. 2) – or what we would describe as 'geological restratification'. If restratification is indeed the eventual outcome of materials that have been destratified, as Anthropocene science recognizes there is a great deal of lateral

transfer and transformation that intervenes between their original unbinding and their later re-deposition. Like extractive industries themselves, much of this rearrangement is intended by human agents: this includes transportation, processing, utilization, and some forms of disposal. But much of it – including byproducts, leakage, decomposition – is largely unintentional. The collision between rapidly changing Earth system processes and de-stratified materials greatly exacerbates the level of unpredictability in this circuit between de-stratification to re-stratification. These interruptions, we argue, take on a special significance with the recognition that entire landscapes have been made over in the interests of intensifying mineral and energy extraction.

The paper offers a conceptual mapping rather than a quantification of the negative synergies between geological de-stratification and Earth system change. We construct a typology of four categories of ‘trouble’ that is not intended to be exhaustive. The first category, illustrated by our opening example, is the interaction between shifting fire regimes – or pyroclimatic change (Biondi et al., 2011) — and processes of hydrocarbon extraction. The second is the interface between hydroclimatic change – which includes intensifying hydro-meteorological events and sea level rise – and hydrocarbon energy infrastructure. The third category is the interrelationship between hydroclimatic change and landscapes of mineral extraction. Our fourth category brings together impacts of pyroclimatic and hydroclimatic change on nuclear infrastructures and on landscapes already contaminated by radioactive materials.¹

We begin with an overview of existing ways in which social science and humanities scholars have sought explain the specific forms of hazard that afflict modern or late-modern societies. This includes theorists who prioritize risks deriving from complex ‘horizontal’ socio-technical arrangements and those who focus more on ‘vertical’ interactions with the layered structure and deep temporalities of the Earth. We suggest, however, that Anthropocene sciences offers vital insights for bringing together the horizontal and vertical dimensions of these narratives – noting in particular the deepening collaboration between ‘hard rock’ geology and Earth system science.

Following our schematizing of an Anthropocene species of trouble, we return in more depth to the question of how to understand the escalating collision between Earth system change and geological de-stratification. Going beyond a framing of this predicament as a management problem, we make a case for probing the deep historical origins of human capacities to negotiate between the Earth’s surface and subsurface. As an opening for later explorations, we propose that Anthropocene science’s novel focus

on the articulation between Earth System flows and lithic strata has as yet untapped potential for theorizing the long-term human acquisition of geological agency.

Diagnosing Modern ‘Species of Trouble’

There is an extensive social science and humanities literature diagnosing particular kinds of hazard associated with the conditions of what has been termed ‘late modernity’. By the mid-to-late 1980s, a series of high-profile accidents such as Three Mile Island, Bhopal and Chernobyl had sufficiently shocked social thinkers to the extent that analyses of techno-environmental risk moved from the margins to the mainstream of social inquiry. Echoing themes raised earlier by biologist Rachel Carson (1962), sociologist Kai Erikson identified a ‘new species of trouble’ characterized by the accidental release of toxic substances ‘that seem to work their way stealthily in the tissues of the human body and the textures of human life’ (1994: 20). Fellow sociologist Ulrich Beck proposed that increasingly deep-seated interventions in atomic, chemical, and biological processes are accompanied by the ever-present possibility of ‘undelimitable’ accidents that, once triggered, resound unstoppably through space and time (1995: 76-9). Seeking to identify the precipitating conditions of what he referred to as ‘normal accidents’, sociologist Charles Perrow (1984) alighted upon the effect of routine and minor malfunctions concatenating through complex, tightly coupled socio-technical systems. More generally, Bruno Latour (1993) and fellow science studies scholars suggested that the modern world lacked conceptual frameworks through which to understand its own intensifying intermixing of social and natural components (see also: Bennett, 2005; Law and Mol, 2008).

While these analyses focus on a predominantly ‘horizontal’ interconnectivity and complexity, concern with the dangers arising from fossil fuel and mineral extraction has also prompted approaches of a more ‘vertical’ disposition. As well as addressing the infrastructures through which extracted materials circulate, this work looks at how modern exploitation of the subsurface opens up spatiotemporal relationships that are radically different from those that characterise most surface processes. As political theorist Timothy Mitchell explains: ‘fossil fuels are forms of energy in which great quantities of time and space ... have been compressed into a concentrated form’ (2011: 15). Geographer Gavin Bridge (2009) likewise recognises that the mineshaft or well is a portal to stores of energy and minerals that have accumulated over vast stretches of geological space and time. The Earth’s surface and subsurface, Bridge attests, are ‘two worlds in which time and space work differently’ (2009: 45), and the speed at which this

vertical divide has been breached is one of the defining features of modern existence. ‘The shock of modernity,’ he observes ‘... is in part about the radical mixing together of these two different planes’ (2013: 56, see also: Bremner, 2013; Clark, 2017).

Bridge acknowledges his debt to cultural historian Lewis Mumford’s earlier account of ‘carboniferous capitalism’ (1934: 156-8). Not only did Mumford argue that the unprecedented rush of geologically ancient matter-energy was a key to understanding the exploitative social and economic relationships of modern industrial capitalism, he also recognized that entire landscapes of despoliation were the inevitable outcome of the extractive mind-set. ‘The byproducts are a befouled and disorderly environment’, Mumford concluded, ‘the end product is an exhausted one’ (1934: 157).

Aspects of this vertical approach to late-modern trouble will likely strike chords with geoscience researchers, from whom much of this work borrows. At the same time, Anthropocene science has its own version of the more horizontal narrative, as for example when Will Steffen and his co-authors observe: ‘When the hyper-connectivity of the human enterprise intersects with the pressures on Earth System goods and services, some concatenated global crises can propagate rapidly through the Earth System’ (Steffen et al., 2011: 741). The social science research into late modern catastrophes that we have outlined has much to offer Anthropocene science, especially with regard to teasing out the connections between hazard-inducing conditions and uneven relations of power and wealth, and exploring the processes through which hidden dangers come to be rendered visible and turned into occasions for political mobilization.

There is, however, a vital aspect of the dynamics of contemporary disaster about which social scientists could learn a lot from Anthropocene science, and we would add, where the community of Anthropocene researchers themselves might do more with their own boldest epistemic innovations. Whereas the ‘horizontal’ and ‘vertical’ strands of social science investigations of late-modern catastrophe have yet to be systematically integrated, exploring the interaction between the outer Earth system and the lithic strata that compose the Earth’s crust has emerged as a definitive theme of Anthropocene natural science inquiry. Unprecedented collaboration between the newer interdisciplinary field of Earth System science – focused upon ‘the analysis and understanding of contemporary global change’, and that more ‘traditional’ discipline of geology – ‘overwhelmingly concerned with ancient, pre-human rock and time’ (Zalasiewicz et al., 2017: 85) has proved pivotal to the Anthropocene hypothesis. As Zalasiewicz et al. conclude ‘(g)eologists ... benefit from this mutual exchange with Earth System Science,

as it enables better process models of the stratigraphical data' while benefits to Earth System science accrue from 'the recognition of geological signals as additional and proxies...especially for testing models and forecasting future scenarios' (2017: 97, see also Steffen et al., 2016). We would suggest that this idea of the hinging together of Earth system and lithic strata is at once literal and deeply imaginative; a powerful conceptual tool and a potent metaphor (Rickards, 2015).

It is noteworthy that one of the most influential Western philosophical texts of the latter 20th century performs a similar move of putting strata and flows into conjunction. In *A Thousand Plateaus* (1987) Gilles Deleuze and Félix Guattari explore the human capacity to move across different strata and to work the contents of these strata into new structures and mixtures (335, 502-3). Their term for this process - which we have borrowed - is 'destratification'. While geological strata are only one of the several types of sedimented and relative inert compositional layerings with which Deleuze and Guattari engage, it is clear that geology provides the original form and the model for other kinds of stratification and destratification (1987: 40-5). Their concern with the way that, under certain circumstances, the contents of strata come to be released and enter into relatively unbound and faster moving flows and circulations now appears remarkably prescient of key conceptual moves of Anthropocene scientific thought (see: Clark, 2017; Saldanha, 2017: 23-6; Yusoff, 2017). If in a speculative way, Deleuze and Guattari's warning about the risk of 'too-sudden destratification' stands, for us, as an early incitement to think the vertical and horizontal dimensions of endangerment together (1987: 503).

Informed in part by the different modes of addressing the horizontal and vertical dimensions of modern 'trouble' outlined in this section, we turn now to a range of real-world situations characterized by negative synergy between Earth system change and destratification of geological materials

Varieties of Earth System Change-Geological Destratification Trouble

In each of the four categories outlined, we set out from the mounting evidence that uneven anthropogenic impacts are already pushing the operating state of Earth system out of Holocene conditions. We also take as given that geological destratification has been so intrinsic to modern and some non-modern ways of life that it has transformed entire landscapes. Our focus, then, is on the further turn of the spiral: how escalating Earth system change reacts back upon extensively upturned or redistributed geological materials.

Pyroclimatic Change and Hydrocarbon Extraction

There is evidence that climate change is increasing wildfire events in many regions, although the global picture is complicated and includes indications of decreased fire activity in other regions (Bowman et al., 2013; Jolly et al., 2015). Recent research predicts a ~50% increase in lightning strikes in the USA over the 21st century (Romps et al., 2014), while a Canadian study demonstrates that temperature-induced drying of forest fuel layers alone will result in a significantly higher frequency of extreme fire weather days, (Flannigan et al., 2016). In 2016, just months after the latter study was published, record warm temperatures saw the outbreak of some 330 wildfires in the Canadian province of Alberta (McGrath, 2016), including the Fort McMurray fire that burned from May 1-July 5 and spread across 1,500,000 acres. Fort McMurray is the service centre of the Athabasca oil sands operations where bitumen is extracted on a massive scale. While bitumen itself is relatively inflammable, subsequent research highlighted that natural gas and other highly flammable substances involved in the extraction, processing and transport of bitumen are at high risk of ignition by wildfire, although in this case extensive firebreaks of clear-felled forest sufficed to insulate mining infrastructure (Khakzad, 2018; Khakzad et al., 2018).

Exposed coal seams and peatlands, especially when the latter are degraded, are more flammable than bitumen. Coal-seam fires have been igniting naturally for millions of years but have become much more common as a result of the global spread of mining since the Industrial Revolution. Reports from China suggest that coal fires covering over 30 km² are currently burning - amounting to an annual loss of up to 200 million metric tons of coal (Kolker et al., 2009; Song et al., 2014; see also: Yan et al., 2020) – while at last count 32 abandoned coal mines in the USA were alight (Kuenzer and Stracher 2012). The coal and peat fire problem is especially acute in Indonesia where it is exacerbated by extensive fire-driven forest clearance for plantation farming (Gaveau et al., 2014; Whitehouse and Mulyana, 2004). One study conjectured that there were over 110,000 coal and peat fires in Sumatra alone (Hamilton et al 2000), while it is estimated that peatland fires in the extreme 1997-8 fire season generated the equivalent of 40% of that year's global fossil fuel carbon emissions (Chokkalingam et al., 2005).

Feedback effects abound. Climate change dries out peatlands, leaving them more flammable (Merchant 2015). Particulate pollution from fires in Indonesia and other regions reduces rainfall and intensifies the El Niño effect – in turn increasing forest flammability (Herawati and Santoso 2011; Mayer 2006). Coal fires ignited by wildfire

smolder for decades or centuries, all the while serving as ignition sources of subsequent fires (Goldammer, 2007). Fire in underground mines causes subsidence that may further open seams to oxygen, leading to propagation of wildfire (Whitehouse and Mulyana, 2004; Krajick, 2005).

Along with the greenhouse gas carbon dioxide, coal fires also emit toxic levels of carbon monoxide, sulphur dioxide, arsenic, fluoride, mercury, lead and selenium, which enter food chains and threaten human health (Dontala et al., 2015; Melody and Johnston, 2015). There is also evidence that wildfires can release significant quantities of industrial lead and other toxins that vegetation has absorbed over decades of exposure to the combustion of fossil fuels and their additives (Kristensen and Taylor, 2012). At larger scales, black carbon sediments from the coal fire-wildfire nexus contribute to the melting of Arctic ice sheets, adding to sea level rise (see: Keegan et al., 2014).

In many regions intensifying wildfire also threatens electricity transmission infrastructure (Sathaye et al. 2011: 6, 38), although this problem is obviously not restricted to hydrocarbon-generated electrical power. In turn, faulty powerlines have sparked numerous wildfire outbreaks (McFall-Johnson 2019).

Hydroclimatic Change and Hydrocarbon Infrastructure

Many coastal regions are already showing impacts of climate change (Burkett, 2011). Even in the unlikely case that greenhouse gas emissions are leveled, oceanic thermal inertia will ensure that sea levels continue to rise, with conservative estimates pointing to an eventual 2.3 meter rise per Celsius degree of global warming (Levermann et al., 2013). Compounding the effects of rising sea levels on coasts are more frequent and intense hydro-meteorological events including stronger storm surges (Brown et al., 2014).

Much hydrocarbon-based energy infrastructure, including refineries, storage depots, tanker terminals and pipelines, is concentrated in coastal zones, with recent studies suggesting high levels of vulnerability coupled with limited planning for climate change (Brown et al., 2014; Carlson et al 2015). This is currently best documented in the USA. In some regions, such as the Gulf Coast, sea level rise is exacerbated by subsidence resulting in part from oil and gas extraction (Carlson et al., 2015; Kolker et al., 2011), while in southern Louisiana canalization of waterways by the oil industry has opened up a channels for incoming storms and surges that locals refer to as the ‘hurricane highway’ (Bakker, 2005).

During the record-breaking 2005 Atlantic hurricane season, Hurricane Katrina destroyed or set adrift 45 oil platforms, while Hurricane Rita destroyed another 69 platforms (Kaiser 2015). Despite rigorous new design standards, the 2008 season saw Hurricanes Ike and Gustav take out a further 60 offshore structures (Larino, 2015). 1992's Hurricane Andrew damaged 480 offshore pipelines, 2004's Hurricane Ivan reportedly damaged 160, and Hurricanes Katrina and Rita another 457 (Burkett, 2011: 7722). Katrina resulted in spills of some 6.7 million gallons of fuel from onshore installations, with a single facility in southern Louisiana spilling 25,000 barrels of oil – which contaminated city canals and approximately 1,700 homes (Carlson et al., 2015). In the course of the Atlantic Coast's Superstorm Sandy in 2012, flooding, dislodged buildings and uprooted trees caused over 1600 pipeline leaks in New Jersey's Barrier Islands alone (Groeger, 2012). Hydrometeorological events can also trigger fires and explosions, as a result of lightning strikes and the puncturing of pressurized flammable vapours and liquids (Cruz et al., 2001)

While the oil drilling platforms on the outer continental shelf of the Gulf of Mexico have apparently been designed to accommodate storm surges, they are not built to withstand permanent sea level rise (Burkett, 2010). Onshore infrastructure is no better placed. One survey identified nearly 300 US coastal energy facilities located below 4 feet from high tide level, with Louisiana alone having over 100 facilities – mostly oil and gas – sited less than 1 foot below local high tide (Strauss and Ziemiński, 2012). As an increasing proportion of the world's conventionally recoverable oil and gas lies in 'difficult environments', infrastructure faces other problems – such as drought and thawing permafrost (Hopkins, 2007). Extensive oil and gas networks in Russia's oil-rich north already face major thaw-related damage and deformation problems, with a 2010 study reporting some 35,000 pipeline accidents a year in West Siberia (Sobczak, 2015).

As in the case of pyroclimatic hazards, escalating hydroclimatic extreme events threaten electricity transmission (Sathaye et al., 2011: 6). In addition to the vulnerabilities of fixed infrastructure, hydrocarbon global supply chains rely on the mobile infrastructure of ocean-going vessels that – while they may benefit from decreased sea ice – are exposed to intensifying extreme weather events (Bitner-Gregersen et al 2012).

Hydroclimatic Change and Mineral Extraction

Although the harmful consequences of mining have been documented for centuries (see Agricola, 1950 [1556]:6-8), it is only in the closing decades of the 20th century that the

enduring risks posed by mineral ore extraction have been fully appreciated (Carvalho 2017). Some ores, including zinc and copper, generate acids when exposed to air, water and microbial life, while other ores are frequently associated with both acid-generating minerals and heavy metals (Carvalho, 2017; Laurence, 2011; Lin, 2012). Most metal ore extraction generates large amounts of waste rock – removed to access ores, and tailings – which are the waste product of ore processing: the sulfate minerals in the latter being particularly reactive due to their fine grain (Lin, 2012). Along with chemicals such as acids and cyanide used in processing, tailings can contain dozens of elements including arsenic, lead, and mercury in concentrations that can be highly toxic to ecosystems and organisms which have not evolved to tolerate such exposure (Franks et al., 2011; Earthworks and MiningWatch, 2012: 2). Acid mine water and other dangerous chemical constitute a vast problem, exacerbated both by exponential increase in demand for many ores and by the fact that such demands push extraction into lower grade and less accessible ores, resulting in larger void spaces, deeper shafts and ever higher waste to ore ratios (Bridge, 2009; Mudd, 2010).

Both the mass of waste generated by mineral extraction and the tendency of extractive industries to mine sites beyond profitably and then to relocate are posing considerable challenges to regulatory frameworks. As Mudd observes in the Australian context: ‘(a)t present, there is no compulsory requirement for public reporting of the waste rock mined annually, nor it’s nature’ (2010: 110). Others note how decommissioned mines and other extractive sites frequently escape monitoring and legal title (Laurence, 2011). It is onto this already crisis-ridden situation that we must layer the impacts of climatic and Earth system change.

As with hydrocarbon energy systems, most mine and quarry infrastructure design assumes stable climate or at least continuation of past variability (Ford et al., 2011; Hull and Ghiassi-Razavi, 2010). In the mining industry, researchers anticipate that climate change will impact slope stability, tailings, and water retention – with severe consequences for the dispersion of toxic residues (Anawar, 2015; Pearce et al., 2011; Northey et al., 2017). Hydrology is the key variable, and both drought and heavy rain playing critical roles in shifting spatial dispersion of contaminants (Ackil and Koldas, 2006; Foulds et al., 2014; Loechal, 2013). Catastrophic failure of tailings dams, such as the 2015 Mariana and 2019 Brumadinho disasters in Brazil, are a particular problem. As Holden (2015: 455) notes: ‘(t)ailing dams must now be constructed to accommodate worst case scenarios Given the uncertainty surrounding the rapidity of climate change, determining worst case scenarios will be extremely difficult if not impossible’.

Further problems have been identified with coastal mines at risk of sea level rise (Holden, 2015: 252), and in arctic regions where thawing permafrost subverts assumptions that mining waste can be permanently stabilized by freezing conditions (Hird, 2017; Northey et al., 2017). Accelerating geochemical weathering rates resulting from increased temperature variation can also trigger mass movement of rock in current or former mining sites (Northey et al., 2017; Phillips, 2016; Rayne et al., 2009).

In regions where extractive histories run to centuries or millennia, shifting river systems are remobilizing contaminants from old mining works and floodplain sediments (Foulds et al., 2014). Evidence that ancient mining sites like the Rio Tinto estuary are still highly contaminated after 4500 years is a reminder of the persistence of mining-related pollution (Franks et al., 2011; SCU, 2013: 7), leading commentators and legislators to insist that some kinds of mining waste need to be closely managed *in perpetuity* (Franks, 2011; Kempton 2010). How this is to be achieved given accelerating climatic and Earth system change is unclear. As Phillips concludes: ‘the potential increase in acid mine drainage and heavy metal pollution due to climate change, could very well be beyond any original, current or foreseeable design parameters of mining operations and infrastructure’ (2016: 98). At present, normal practice is to mark it and forget (Kearnes and Rickards 2017).

Hydro- and Pyroclimatic Change and Nuclear Infrastructure

Mined from crustal rock, the naturally radioactive heavy metal uranium can be used in sustained nuclear chain reactions to generate power. With its combined chemical toxicity and radioactivity, uranium is implicated in a range of adverse health effects when incorporated in biochemical processes. These are compounded by bioaccumulation, transference along food webs, and intergenerational transmission (Dewar 2015; Pereira et al., 2014), making radioactive contamination a quintessential ‘slow emergency’ (Anderson et al. 2019). While nuclear power is celebrated in some quarters as a low carbon form of energy, the 2011 Fukushima Daiichi nuclear disaster triggered by the Tōhoku tsunami has had knock-on impacts in the nuclear industry by exposing the vulnerability of nuclear infrastructure to climate or Earth system change (Jordaan et al., 2019; Krausmann et al., 2019).

Few of the world’s 430-plus operational nuclear power plants were constructed with climate change in mind, leaving many exposed to the potentially catastrophic effects of storm surges, drought, floods, heatwaves, wildfire and sea level rise (Bartos and Chester,

2015; Jordaan et al., 2019;). Generally positioned close to water bodies for cooling purposes, the vulnerability of reactors to hydro-meteorological extremes has been made increasingly apparent by events such as the 1999 storm-surge that knocked out safety systems at France's Blayais Nuclear Power Plant (de Fraguier, 2010; Kopyotko and Perkins, 2011), and the flooding during Superstorm Sandy that threatened water intake systems at New Jersey's Oyster Creek and Salem plants (Shifflett and Sheppard, 2014). However, the international treaties and standards that regulate construction and operation of nuclear facilities have yet to seriously consider impacts of climate change (Jordaan et al., 2019), an oversight that extends to nuclear waste management. Most of the 80,000 metric tons of radioactive spent fuels thus far generated in the US is stored 'temporarily' at power-plant sites — many of which are vulnerable to sea level rise (Jenkins et al., 2020).

It takes some 440 thousand tonnes of excavated uranium-bearing rock to produce the 30 tonnes of uranium required annually to fuel the average 1200 MW nuclear reactor (Dimercan, 2020). While attention has been focused on high-level threats to nuclear reactors, climate change is also likely to mobilise toxins and radiological agents at current and past uranium mining sites (Pereira, 2014). Wildfires also pose considerable risk to uranium mines in many regions, and firefighters face hazardous radiation exposure when fighting blazes in abandoned, reforested mining landscapes (Mingingawreness, 2015). When a prescribed burn during a three-year drought in New Mexico escaped control in May 2000, the resultant conflagration destroyed part of Los Alamos National Laboratory and narrowly missed stockpiled radioactive material (Rothman, 2005).

When nuclear accidents such as the 1986 Chernobyl disaster leave surrounding areas unsafe for human habitation, ecological succession in abandoned forests and farmland can create conditions conducive to wildfire (Hao et al., 2009). Between 1993 and 2010, there were over 1000 uncontrolled fires in the Chernobyl Exclusion Zone, resulting in resuspension and widespread redistribution of more than a dozen different kinds of radionuclides sequestered in grassland, peat and woods (Hohl et al., 2012: 2, Yoschenko et al., 2006). While the International Nuclear and Radiological Event Scale was not designed for forest fire releases, estimates suggest that some post-Chernobyl wildfires released enough radionuclides into the atmosphere to qualify as 'serious incidents' (Evangelidou et al., 2016). As with the pyroclimatic change discussed above, longer, drier summers may already be increasing fire risk in the Chernobyl Exclusion Zone (Eördögh, 2014, Evangelidou et al., 2016). Though considered lower fire risk than the Ukraine,

radioactively contaminated forests in Japan's Fukushima prefecture have already experienced significant wildfire outbreaks (Bird and Little, 2013; Digges, 2017).

Human Agency at the Earth System-Strata Interface

It is crucial to keep in mind just how extensive the agency of (some) humans has been in turning the Earth's crust inside out. Geologist Jan Zalasiewicz and his co-authors make the point that anthropogenic mixing or 'turbation' of rock fabric has so outstripped the impacts of any other organism that it has 'no analogue in the Earth's 4.6 billion year history' (Zalasiewicz et al., 2014: 4). Indeed, they add, such is the degree of cross-cutting of strata by our species that it unsettles the logic of superposition through which geologists conventionally make sense of the Earth's deep history (Zalasiewicz et al., 2014). It is telling that such observations resonate with the definition of existential disaster in certain traditions of 20th century Western philosophy: that is to say an event of such consequence that it threatens the very language or reasoning through which the event itself could be made intelligible (Blanchot, 1995: 1-7; Lyotard, 1988: 56).

The emphasis of our paper on how Earth system change is impacting back upon de-stratified geological materials is more than a matter of the sheer magnitude of rock fabric disruption. It is also about the reach, scale and complexity of infrastructure devoted to exploiting subsurface deposits: the millions of miles of tunnels, pipes and boreholes, the vast number of facilities and installations, the making over of entire landscapes for extractive purposes (Haarstard and Wanvik, 2017; Labban, 2014; Zalasiewicz et al., 2014). Central to any analysis of the interactions between Earth system change and anthropogenic de-stratification is the growing recognition that the excess or remainder of mineral-energetic extraction is at least as consequential as its intended effects. As Hird notes '(b)etween 95 to 99.9995 percent of mined ore is considered waste' (2017: 198), a realization that has led commentators to conclude that mining is more a matter of waste-disposal than it is of resource acquisition (Bridge, 2009).

By definition, de-stratification releases materials deposited and transformed over deep geological time into radically different ecological or geophysical contexts – which is the basic reasoning behind demands for long-term if not perpetual management. The re-deposition of such material plays a significant part in the formation of novel anthropogenic strata that is so central to the Anthropocene narrative (Zalasiewicz et al., 2019: Ch. 2). Whereas formalization of the Anthropocene hypothesis requires

identification of a distinct, geosynchronous signal in ‘restratified’ material, our own concern with the collision between destratified landscapes and Earth system change bypasses this process in the interest of prioritizing the risks and hazards this involves. So serious are these threats, we are arguing, that they call for a fundamental rethinking in the current globally dominant social relationship with the vertical or three-dimensional Earth.

Again and again, the work we have reviewed underscores the inadequacy of regulatory frameworks for dealing with waste and other collateral impacts of human mass geological transfer. As geochemist Houston Kempton and his co-authors understatedly conclude: ‘(a) search for existing institutions capable of providing long term mine management is discouraging’ (Kempton et al., 2011: 563). This is hardly surprising, given that the basic operative principle of modern industrialized extraction, as we noted above, is one of exploitation, exhaustion and abandonment (Bridge, 2009; Mumford, 1934: 156-8).

Not only do policymakers routinely underestimate the deep temporal repercussions of geological transfer, but the very logic of the global capitalist economy rewards extractive operators who privatize resources while leaving to ‘the public’ the costly and effectively interminable problem of site remediation (see: Carvalho, 2017; Jenkins et al., 2020). Faced with pressures to ‘manage’ waste and related problems, many companies either relocate or disband. Drawing parallels with the nuclear industry, Jenkins et al note that ‘oil and gas companies frequently go bankrupt rather than dealing with cleaning up orphan wells or unclaimed sites’ (2020: 7). And this is even before we factor in requirements for the extractive industries to deal with the large-scale, accelerating and cascading impacts of Earth system change on current or legacy sites (see: Hodgkinson et al., 2014; Loechel et al., 2013).

Many of the social and political issues associated with governance of extractive industries in the current global order have been rigorously analysed (see: Bebbington, 2012; Bridge 2014; Mitchell 2011; Walker and Johnson 2018). Our emphasis on the interaction between geological destratification and Earth system change, however, takes us in another direction. While it’s vital to recall that the irruption of geological transfer over recent centuries belongs to a specific socioeconomic system, it is equally important to consider the deeper historical roots of the human capacity to move between the Earth’s surface and subsurface. It is in this context, we argue, that Anthropocene science’s definitive concern with the articulation between Earth system processes and ‘hard rock’ geology has potential to do more work than it has yet been tasked with.

Well in advance of the emergent *negative* synergies between Earth system change and extractive landscapes we have been cataloguing, the turn to mass geological destratification in the era of industrialization can be viewed in terms of its *positive* synergies with expanding human engagements with Earth systems. Early use of the steam engine to pump water from coal, iron ore and other mines was itself a form of feedback that accelerated extractive processes (Tiles, 2009). This in turn facilitated global synergies between steam-powered machinery used in fabric manufacture and the intensified exploitation of Earth system processes in the form of the plantation economy – which brought together tropical or subtropical climates, plant monocultures and coerced human labour (see Clark and Szerszynski, 2021: 62-4; Protevi, 2009: 165-9; Tsing, 2015: 39-40). In this regard, we can view the steam engine as new kind of hinge or articulation between the mineral-energetic resources of the lithic strata and the largely solar-powered flows of the outer Earth system.

The much earlier emergence of urban centres in the mid-Holocene can also be viewed as a significant development in the anthropogenic hinging together of mineral-bearing strata and Earth system fluxes (Clark, 2015; 2017). In the ancient Middle East, archaeometallurgists have noted, there was a dynamic, self-reinforcing trade relationship between highland metallurgy and the intensive grain cultivation of the alluvial lowlands (Atchison, 1960; 18-24; Yener, 2000: 27). Metals not only provided the material for the tools, weapons, measures and currencies that were key components of the earliest agrarian empires, metallic implements also accelerated mineral ore extraction. Reflecting their distinct but complementary contributions to social life, historian Jack Goody notes that in Mesopotamia, the Earth's surface and subsurface were already subject to political-legal demarcation five to six thousand years ago (2012: 22). A few thousand years later, he adds '(t)he very boundaries of the Roman Empire ... were the result of the distribution of metals, (2012: 80).

In sum, a focus on the different ways in which human agents have intervened at the juncture between the outer-Earth system and the stratified subsurface offers a powerful conceptual tool not only for engaging with the Anthropocene, but for understanding the long history of gradual human acquisition of geological agency (Clark and Szerszynski, 2021: 64-5). At this point its worth recalling that each of the four categories of contemporary negative synergy between Earth system change and geological destratification presented earlier involve some form of fire – whether directly as threat or indirectly in the eventual process of smelting ores or combusting hydrocarbons. If we

are seeking the human capability that ultimately underpins unprecedented impact of our species on both rock fabrics and Earth system processes, it is fire, above all, that appears to be the key (Clark, 2020).

If the unique capacity of the genus *Homo* to handle flame is pivotal to its increasing impact on the living surface of the Earth, so too is fire-use central to the cracking of rock, roasting of ores, the forging of metals and the much later the setting to work of fossil hydrocarbons (Pyne, 2001: 131). Fire use, we propose, is the original anthropogenic hinge between the Earth's surface and subsurface, for without its guiding light the subterranean world would have remained inaccessible to a diurnal, surface-dwelling organism (Clark, 2020). It is no coincidence, we would add, that the exceptional human capacity for cross-cutting geological turbation noted by Zalasiewicz et al. (2014) more closely resembles the effects of igneous than biological processes, for already in the ancient world craftspeople were capable of firing their furnaces to the volcanic temperatures of 1200-1300 °C in order to transform the structure of geological matter: this being an axial moment in the anthropogenic hinging together of the surface and subsurface (Clark, 2015; Clark and Yusoff, 2014.).

It is beyond the scope and imaginary reach of this paper to even begin to resolve the current planetary predicament of anthropogenic Earth system change reacting catastrophically upon landscapes made over by accelerating human practices of geological de-stratification. We should not forget, however, that there are plentiful examples of human collectives who have tapped into the resources of the subsurface cautiously, respectfully, even reverently; societies who have looked upon the modern Western proclivity for mass upturning of the body of the Earth with horror (Kopenawa and Albert 2013: 261-289; Li and Paredes Peñafiel 2019, see also: Neale and Vincent, 2017). Much of 'the species of trouble' we have been diagnosing manifests a set of drives and dynamics specific to the global capitalist socioeconomic order: a system whose *modus operandi*, it is often noted, is founded on the principle of extraction to the point of exhaustion (Mezzadra and Neilson, 2017). While there is an urgent need to cut firebreaks in the destructive synergy between Earth system change and exponential extraction, however, we would suggest that transforming the way our species has come to articulate between lithic strata and Earth system now requires nothing less than a rethinking of what it means to be human.

Far from arguing that this is a task best left to social thinkers, we propose that such a project calls for Anthropocene inquiry's revolutionary collaboration of hard rock geology

and Earth system science to be deepened, elaborated upon and generalized. What we face is a critical issue of reining in or dismantling today's most destructive agents of mass geological transfer. But it is also a matter of totally reorganizing the anthropogenic orchestration of the Earth system-strata interface. It is only by thinking generatively *through* this crucial point of articulation, we would argue, that it becomes possible to imagine alternative arrangements. This is a task that requires the input of as many different ways of thinking and doing human geological agency as we can gather together.

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¹ Each of our categories overlaps with research in the field of ‘natech’ accidents: the study of impacts of natural hazards on hazardous industry and infrastructure (Cruz et al., 2006; Krausmann et al., 2019), although our interest is in the anthropogenic dimension on *both* sides of the convergent catastrophe. In a more general sense, our approach might be seen as a subset of the study of the interacting and concatenating impacts of physical and social drivers of hazard in the emergent field of inquiry into ‘compound’ or

‘connected’ events (Zscheischler et al., 2018; Zscheischler et al., 2020; Raymond et al., 2020) – with our own particular stress on the stratal or vertical dimension of such events.