Planetary Cities: Fluid Rock Foundations of Civilization

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In its English variant, the phrase 'nose to the grindstone' has been tracked to the 16th century, but its provenance ought to be much older. Excavations of the 2nd Millennium BCE city of Elba in contemporary Syria revealed a veritable production line of grain-grinding stones and rollers, some fifteen in a single room, a spatial plan redolent of routinized, disciplined labour. In this arrangement we might glimpse the nascent diagram of a 'biopower' that includes the forces of life itself and specifically human strategies for harnessing and entraining these forces (Foucault, 2007: 1-2). But so too do we catch the traces of what Elizabeth Grosz calls 'geopower', the inhuman forces of the Earth and cosmos that humans and other artful living beings also tap into and set to work (Yusoff et al, 2012; Grosz et al, 2017).

In the earliest cities, these incipient bio- and geopowers appear concurrent and co-constitutive. The kernels that were painstakingly pulverised in Elba, the grain that put flesh on the bones of the agrarian labour force, would most likely have been grown in alluvium – clay, silt and sand laid down on the rocky bones of the Fertile Crescent by the great force of the Earth's sedimentary cycle. And just as the powers of human and other organismic bodies were being subjected to supervision and management, so too was fluvial geomorphic power emerging as an object of monitoring and regulation.

The city can be viewed as an especially intense site of human exploration and actualization of these deeper geopowers. Whereas recent urban theory, developing Henri Lefebvre's later work, suggests that we must now consider 'the imprint and operationality of urban processes on the planetary landscape' (Brenner, 2014: 15), I want to make the case that we should also think of cities as 'planetary' from their very outset. The urban centres that emerged on Mid-Holocene alluvial plains, I argue, channeled dynamic geological processes. More specifically, they positioned themselves at vital thresholds or junctures in this planetary dynamism: the shifting, unstable ground from which they constituted themselves being the fluid-solid phase transition between hard rock and flowing particulate matter.

In the context of early riverine social formations, however, this kind of 'planetary thinking' has important predecessors. In his theory of hydraulic civilization, Karl Wittfogel (1963) explored the significance of the capture and diversion of water to enable crop cultivation in river-fed regions where rainfall was inadequate to sustain intensive agriculture. Still too often censured for his environmental determinism, Wittfogel might better be seen as having inherited and developed a lineage that takes seriously the physical properties of water: its sources, volumes, periodicities and mobilities. In this way, he conjoined the question of the formation and the composition of a certain type of urbanism to a consideration of the hydrological processes that are central to the functioning of the Earth as a geological or planetary system.

Less in need of denaturalizing, what Wittfogel's hydro-centric approach could do with is a deal more muddying. For as geomorphologists remind us, '(i)t was the materials that rivers carried, as well as the water they delivered, that determined river potential for long-term civilized societies' (Macklin and Lewin, 2015: 230). And this debt to sedimentary processes goes beyond human life, and even life in general. So significant is fluvially transported particulate matter to shaping the Earth, geologist Jan Zalasiewicz contends, that in relation to the rest of our solar system, 'one might … denote this planet as the muddy planet, for it is the only one to be encased in a thick shell of mud and mudrock' (2008: 22).

'Mud' is made up of fine-grained sediments – silts, sands, clay – and organic matter, suspended in water. Just as milling grains produces granules fine enough to be mixed with fluids, so too does the pulverisation, by elemental forces, of solid rock into particles enable their admixture with turbulent water or air. Intercepting a tiny proportion of the planet's vast muddy traffic, early floodplain civilizations succeeded in fashioning worlds that were relatively enduring – and in some cases remarkably long-lasting – out of mud's inherent transience and formlessness (Hassan, 1997).

But intervening in fluvial geomorphic processes was not the only form of human earth-shaping activity taking place in the ancient Fertile Crescent. In the early 1990s, archaeologists excavating the four-thousand-year-old Mashkan-shapir site, in current-day southern Iraq, came across a cache of grindstones that looked and felt like basalt – the hard, fine-grained rock that issues from volcanic eruptions. However, tests indicated that the rock, which also appeared to have been used as construction material, was not of volcanic or 'igneous' origin. Without ready access to solidified magma, it would seem, artisans living on the floodplains between the Tigris and Euphrates rivers had effectively made their own volcanic rock. As Elizabeth Stone and her colleagues explain: 'synthetic basalt appears to have been manufactured in some quantity as a substitute for the natural basalt that had been used for grinding grain in all parts of the ancient Near East since the beginnings of agriculture' (Stone et al, 1998: 2092)

Analysis indicates that it would have taken kiln temperatures of around 1200 °C – the approximate heat of magma in a volcano – to have achieved 'liquidus' or complete melting of alluvial silt, after which the molten matter looks to have been left to cool for 20 to 40 hours to allow crystal growth to occur (Stone et al, 1998: 2092). For Stone et al, what is of foremost interest here is not the novelty of 'anthropic rock' production so much as the broader spectrum of practice upon which Mashkan-shapir's artisans would have drawn. 'Material compositionally identical to synthetic basalt', they conclude, 'was a by-product of the ceramic and metallurgical industries before the second millennium B.C.' (1998: 2093).

Early-to-mid 20th century archaeometallurgists were as keen to foreground the contribution of metalworking and other pyrotechnological arts to early civilizations as was their contemporary Wittfogel to stress the importance of hydrological engineering. These metallurgical researchers were the first to draw attention to the vital convergence of the mining-metalworking skills of pastoral peoples from the 'metaliferous' highlands around the Fertile Crescent, with the burgeoning capacity of river valley populations to produce surplus grain (Childe, 1936: 119; Aitchison, 1960: 18). But most of all they were intrigued by the way that ancient metallurgists had discovered how to use high heat to guide mineral ores through a series of transformations that resulted in materials with very different properties than those that entered the 'fiery furnace'.

Analogous to the human harnessing of sedimentary processes, metallurgy hinges upon managing phase transitions between solid and fluid (in this case, molten) – states of matter. What I propose, then, is that ancient riverine civilizations are constructed on the shifting foundations of *two* great Earth-shaping forces: not only sedimentation's dynamical interchange between rock and flowing particulate forces, but also the melting and recrystallization of solid rock that defines igneous processes. In this way, I take Manuel De Landa's council in considering that such geological dynamics might hold 'some of the keys to understanding sedimentary humanity, igneous humanity, and all their mixtures' (1997: 70).

Flood and molten heat, it hardly needs to be said, are threats faced by many contemporary cities. If we are to reimagine the urban under the shifting planetary conditions that have been shorthanded as the Anthropocene, I would argue, we need to extend our gaze far beyond the range of modernity. In dialogue with other formulations of planetary urbanization, the paper proposes a conceptual framework of 'planetary thought' with the aim of foregrounding how the earliest cities came into being through their channelling of sedimentary and igneous processes. Focusing on collective engagement with specific fluid-solid phase transitions, I suggest, can help us to see how 'the planetary' is enfolded into everyday urban life, and conversely, how the lived experience of the city opens out into the dynamism of the Earth. Closer attention to skilled social intervention at fluid-solid interface in ancient urban spaces, I conclude, serves as a point of departure for rethinking the fluvial and fiery challenges faced by today's cities.

Earthly Cities, Planetary Thought

Today, revitalised thinking around 'civilization' and the question of the city increasingly hinges around recognition that urban trajectories are inseparable from the fate of the global environment, or as Manuel Castells put it, '(o)ur blue planet is fast becoming a predominantly urban world' (cited in Brenner and Schmid, 2014: 734). Drawing on Lefebvre's proto-Anthropocenic posing of the 'question of producing planetary space as the work of the human species' (2009: 206), the contemporary thematic of 'planetary urbanization' is explicit in its confrontation with the global ecological implications of a largely urbanized world. This conceptual suturing of the *planetary* and the *urban* conceives of a transformative urbanization that now demands, in Neil Brenner's words, 'systematic consideration of the tendential, if uneven, operationalization of the entire planet – including terrestrial, subterranean, oceanic and atmospheric space' (2014: 20-21).

Lefebvre in turn acknowledged his debts to fellow philosopher Kostas Axelos, and especially to his untranslated 1964 book *Vers la Pensée Planétaire*. Noting how we have come to conceive of the Earth as 'a unity of cycles, self-regulating, stable systems: waters, winds, air, light, soils, and sediments' (2009: 255), Lefebvre pondered the consequences of the way technological modernity sought to capture this imagined spherical closure, cyclicality and equilibration in its own totalizing operations. 'Mastered, captured in concrete and steel, a source of harnessed and trapped energies,' he mused (2009: 256), earthly forces were bound to reassert their own difference, partiality, incompatibility. While his planetary turn arrived just ahead of scientific claims that there are critical thresholds in the functioning of Earth systems, we might see Lefebvre as already on the way to affirming a play of planet and cosmos that broke with the imaginary of closed systems and unicity: a kind of nascent planetary thinking that, with help from Axelos, reached towards the idea that the philosophical question of the 'relation between unity and multiplicity' might extend to the Earth itself (2009: 257).

When sizing up 'planetary thought', we should not forget Donna Haraway's wariness about 'the god trick of seeing everything from nowhere' (1988: 581), a cautionary note that resounds in recent censure of the planetary urbanization thesis for its insufficient attention to the lived and variegated experience of the city 'from below' (Derickson 2015: 648-50; see also Oswin 2018). I want to take a different tack, however, and suggest that planetary urbanization doesn't go far enough in its thinking about and through the Earth, while at the same time insisting that contextualizing thought and practice within the dynamism of the planet is a vital extension of the critical commitment to situatedness (see Clark and Szerszynski, 2021: 49-52).

For all their spirited uptake of Lefebvre's urban-centred socio-spatial thinking, contemporary planetary urbanists seem less willing to advance his nascent thematization of the organization and potentiality of the planet itself. So while the issue of 'what is a city?' is amply addressed, the question of what a planet is or might be goes unasked. It's worth recalling, however, that several decades ago, upon reflection that '(a) new cosmos, together with a new Earth' had been disclosed by the scientific thinking of the 1960s, philosopher Edgar Morin (1999[1993]: 31) had begun to consider human civilization in the context of plate tectonics and other geological forces. Morin explicitly conceived of this 'new Earth' as both living planet and astronomical body composed of deep structural layers of solids and liquids (1999[1993]: 31-2). Concurrently, Michel Serres, spoke of urban agglomerations as 'enormous and dense tectonic plates…. colossal banks of humanity as powerful as oceans, deserts, or icecaps' (1998[1992]: 16-17).

Venturing back to the 1950s, we find Lewis Mumford seeking to reconceptualize urbanism 'from the standpoint of the city's relation to the earth' (1956: 4). Mumford's take on planetary urbanism included such prescient geosocial thinking as the observation that 'the stony outcrop of an Italian hill town involves only a slightly more symmetrical arrangement of the original rock strata' (1965: 3). Half a century later, this willingness to conceptually shuttle between human and geological built environments resurfaces, this time coming from the direction of Earth science. As Zalasiewicz observes, '(b)oth skyscrapers and coral reefs are basically large masses of biologically constructed rock' (2008: 17). Or as he remarks elsewhere: 'we live in and drive on Anthropocene rock constructions that we call houses and roads' (Zalasiewicz et al, 2010: 2230).

While Anthropocene Earth science's take on planetary urbanization is as yet more suggestive than systematic, the real strength of this approach looks to lie in its increasingly accomplished theorization of the interactions between the Earth's geological strata and the more mobile and flowing envelope of the outer Earth (Zalasiewicz et al, 2017). But the interface between lithic crust and outer Earth system is not the only juncture in the planetary body currently under review. As Tim Lenton explains: 'the planet Earth is really comprised of two systems – the surface Earth system that supports life, and the great bulk of the inner Earth underneath' (2016: 17).

Geophysicists remind us that the very existence of an outer Earth is dependent upon the cooling and hardening of rock into an encompassing shell. Thus '(t)he Earth became potentially habitable once it developed a significant solid lid to partition the hot interior from a cooler surface environment featuring liquid water' (Sleep et al, 2001: 3667). The juncture between the outer, more mobile envelope and lithic strata is only one of a series of structural differentiations in the planetary body: the bulk of the Earth's being composed of four bands or layers, three solid and one liquid. The innermost layer, a white hot but solid iron ball, is surrounded by a sphere of liquid iron, followed by the mantle – slow-moving but technically classed as solid, in turn encased by a more conventionally solid crust composed of equally slow-moving plates (Hazen, 2012: 68-9).

The study of other astronomical bodies in and beyond our solar system reveals both that there are great variety of ways in which planets can be composed and that there are generalities in the way this occurs (Summers and Trefil, 2017: 18-19; Lenton, 2016: 139). Gravitational forces determine that planetary bodies organize themselves into distinct layers over time, with the denser elements sinking towards the core. Exactly how a specific astronomical body settles depends on numerous factors including original elemental composition, distance from its sun and events that take place during formation (Clark and Szerszynski, 2021: 79-81). From this perspective the Earth's solid and molten rock layers and its fluid outer envelope are but one manifestation of numerous possible planetary configurations of the solid, liquid and gaseous states of matter-energy. As contemporary planetary sciences confirm, rather than simply stabilizing into a final, enduring arrangement, planets tend to remain dynamic: with such factors as inflowing energy from parent stars, tidal forces from other astronomical bodies, and energy from inner radioactive decay serving to defer final descent into equilibrium (Hernlund, 2016; see also Szerszynski 2016). And so although mature planets may be relatively closed to exchanges of matter, matter-energy traversing the gradients in a layered planetary body continues to generate self-organizing processes.

Such insights, spreading into other disciplines, stimulate the kind of thinking with and through planetary processes initiated by Mumford, Axelos, Lefebvre, Morin, Serres and others. Updating the idea of 'planetary thought' in the light of contemporary geophysical and astronomical inquiry, sociologist Bronislaw Szerszynski (2017, 2018) asks what it might mean for beings like ourselves that we dwell on an astronomical body that maintains the capacity to reorganize itself into novel structural or operational configurations. How then, we might ask, does the ability of a living being, a creature such as ourselves, to learn to do new things relate to our planet's capacity to become otherwise? (see also Clark and Szerszynski, 2021). More specifically, how might thinking in terms of the phase transitions between different states of matter-energy in the dynamics of the Earth help us to make sense of the especially intense bundles of transformative and adaptive activities that occur in dense human settlements?

To truly theorize city life 'from below', I would insist, we must extend our situating of socio-material practices into these processes of planetary structuring and restructuring. The following two sections tease out the idea that urbanism – from its outset – has encapsulated something of our planet's own dynamic interplay of solid and liquid layers. City-shaping sedimentary and igneous interjections, I propose, can be construed as anthropic variations played upon the theme of the Earth's ongoing negotiation between solidity and fluidity, flow and coalescence, melting and recrystallization.

Sedimentary Civilization

'We can never gain a deep understanding of a riverine civilization or make sense of its artefactual repository without a knowledge of the hydrological, depositional and geomorphological dynamics of the river', observes geoarchaeologist Fekri Hassan (1997: 54). As Wittfogel (1963) proposed, the demands of managing large-scale irrigation in the face of naturally variable river flow could (sometimes but not inevitably) push collectives over a threshold into more complex and hierarchical organizational forms. As we noted earlier, subsequent research has supplemented Wittfogel's hydrocentrism with a focus on particulate matter transport (Macklin and Lewin, 2015) – and this work helps us to contextualize socially impacted sediment flux within the broader dynamics of planetary self-differentiation.

The ways in which exposed crustal rock is subjected to weathering and erosion is a central concern of the Earth sciences. Geomorphologists relate how corrosive forces, especially the ongoing onslaught of weakly acidic rainwater, gradually dissembles solid rock into smaller, more mobile materials – or sediments (Smith, 2012). Also conveyed by wind and glaciers, sediments are most often transported by fluid water that is gravitationally driven from higher to lower elevations (see Bremner 2020). In turn, tectonic plate movement generates the gradients that keep water flowing and produces the depressions in which sediment collects – following pathways that change over time as the Earth's crust deforms and reforms (Zalasiewicz, 2008: 14–15).

Rock erosion requires certain conditions for it to occur. Recent experiments have identified critical points at which the shearing force of flowing water moving across a bed of granular rock spontaneously evolves into a mobile state. As Aussillous et al (2016) explain, for erosion to occur, a self-organized phase transition must take place amongst the particles or grains at the microscopic level in order to initiate the processes through which the lattice-like, crystalline structure of rock is broken down and made 'flowable'. But no sooner has crystallinity been unmade than it begins to form again, as electrically charged atoms or molecules jostling in their fluvial environment are drawn towards each other: '(t)he floating ions snap into place, as in a chemical garden, to form microscopic flake-like crystals, a hundredth of a millimetre across or less' (Zalasiewicz, 2008: 21). No longer the old rock, and not yet reformed rock, these tiny recrystallizing clusters are better known as clay – the predominant sedimentary component of mud. And mud, as intimated above, is a vital ingredient of the dense, multi-species, human-orchestrated agglomerations that became known as civilization.

It takes a focus not only on variable water flow but on the dynamic phase transitions between solid and flowing rocky matter, I suggest, to fully appreciate the challenge of constructing durable socio-material edifices on the foundation of intercepted mud. As geomorphologists observe, some ancient Mesopotamian irrigation systems were so effective at distributing sediment-laden water that they have been operative for over five thousand years (Wilkinson et al 2015: 408). But the challenge of managing variable flows and deposition rates, especially in 'muddy rivers' like the Tigris and Euphrates, never lets up. Early communities in Mesopotamia, it has been noted, 'appear to have lived on the cusp between successful management and engineered disaster, and this creative tension may have formed a crucial aspect of human niche construction in the region' (Wilkinson et al 2015: 405)

When they engage with sediment fluxes, we might say, human actors have to reckon with dynamic processes that are doing their own reckoning. Sedimentologists have long understood that fluid flow has a differential impact on variously sized particles. In the words of Wilkinson et al: 'a river overflows its banks so the coarsest sediment will deposit at channel edges while fine sediments will deposit in the floodplain (2015: 400-1). Researchers seek to understand and quantify how this selective transportation and deposition operates – from the erosive stage through to the changing course of a river across a floodplain. As David Gilver and Richard Jeffries aver: '(g)eomorphologists have a responsibility to be able to predict the possibility of altered sediment budgets' – with an eye to assessing 'the possibility of sediment starvation' (2012: 344).

It doesn't take great leaps to imagine the original impetus for such knowledge and the consequences of miscalculation. From the outset, Wittfogel observes, hydraulic societies called for vigilant timekeeping and calendar marking, both to anticipate shifting river flows and to allocate labour to critical seasonal tasks (1963: 29). Crediting Herodotus with identifying the origins of geometry in ancient Egypt's remeasuring of annually deposited alluvium, Wittfogel more generally situates the beginning of astronomy and mathematics in the quest of early floodplain civilizations to find order in an otherwise dangerously changeable cosmos (1963: 29-30).

We can push this idea further and discern more elemental ways that ancient sociomaterial practices resonated with sedimentary dynamics. Most obviously, there is the infrastructural work crucial for trapping and diverting of sediment-rich waters, which required a close working knowledge of the properties of clay, water and soil. In less direct ways, we might also note that mixing fine particulate matter in a fluid medium is the elementary operation common to working with pastes and dough, clay and slip, plasters and cements, and that the hydraulic sorting and stacking of variously sized rock fragments provides the basic diagram for brickwork and stonemasonry.

While the requirement for numeracy may have been closely associated with the administrative demands of emergent grain-fed city-states, it's worth recalling that 'calculus' is the Latin word for pebble, and that the earliest known human calculating device – the Sumerian abacus – appears to have originated from the rearrangement of different sized stones on a sandy ground (Heffelfinger and Flom, 2004-18). Moreover, it has been noted that the originary gesture of writing – rectilinear inscription on a pliant clay medium – reiterates the basic structure of ploughing soil and laying out irrigation systems (Derrida 1976: 287; Porush 1998).

At its core, I am suggesting, civilization is literally sedimentary. 'Sediment' and 'sedentary' share the Latin root *sedere* 'to settle, sit', from the Proto-Indo-European *sed* – 'to sit'. Human sedentarism, like sedimentation, entails physical settling, coming to rest, bedding down. Like the geological dynamics it depends upon, the emergence of large-scale sedentary or urban life is a self-organizing process involving a phase transition between relative fluidity and denser, more-tightly bonded structures. And no less than the transition between solid rock and fluid suspension, social sedentarism tends to be partial and provisional. Archaeologist Anne Porter (2012) stresses the continued importance of the relationship between sedentarism and pastoral mobilism in ancient Mesopotamia, while anthropologist James Scott (2017: 231) draws attention to 'the millennia of flux and movement back and forth between sedentary and non-sedentary modes of subsistence and the many mixed options in between' (see also Clark 2020).

Even the most monumental constructions of the ancient alluvial civilizations – lithification at its most literal – were no exception to this flux. Before they accrued their great symbolic status, prior to their function of keeping enemies and holding labour forces within, the earliest near-eastern Neolithic walls, it has been proposed 'were built in stages as a defense system against floods and mudflows' (Bar Yosef 1986: 161). Or as the Epic of Gilgamesh speaks of Uruk, perhaps the most renowned Mesopotamian fortified city: 'Its towering walls protected it from all sorts of evil, from the armies of enemy kings, from floods, from wild beasts too, and unfriendly gods' (Bryson 1976). But migrating river systems and shifting sediment budgets could set in train the decomposition of even the most grandiose structures. As the Gilgamesh story concludes, without great ado: 'Uruk and its walls slowly crumbled and melted into the earth. Other cities and other languages came into being' (Bryson 1976).

Igneous Urbanism

Once clay has led us from riverbanks to early city-shaping activities we are already moving along a path from sedimentation to another great geological force. Where they are not subject to anthropic interception, most fluvial sediments come to rest in dips or basins – to commence the slow return to solid rock (Bremner, 2020). If a stratum of sediment sinks beneath subsequent layers and is sufficiently compressed and/or heated, its structure will eventually change. But there are faster ways of 'metamorphosing' rock that we've already glimpsed. 'When a clay-mineral rich rock is buried in the guts of a mountain range, it is transformed into a metamorphic rock' explains geologist Simon Wellings (2016). 'Taking clay and baking it in a kiln is the same process – a human created form of metamorphism'.

Human ventures in accelerated heat-induced metamorphosis have been a vital accompaniment to their sedimentary interventions. Pottery vessels aided in the preservation and preparation of agricultural produce, while plasters, kiln-fired bricks and tiles, and later concretes and cements helped to safeguard seeds and grain, to channel and store water, and to manage flows of human bodies in burgeoning urban centres (Clark and Yusoff, 2014). Along with the *products* of the pyrotechnic artisan's kiln or furnace, we need also to consider the *processes* of change. As archaeologist Gordon Childe noted, it is not simply the water-moistened plasticity of clay, but its fiery hardening – 'the conversion of mud or dust into stone' – that imports a novel transmutability into socio-material existence (2003[1936]: 90). But as Childe insisted, still more miraculous are the changes wrought by metallurgy:

> The chemical change effected by smelting is much more unexpected than that which transforms clay into pottery. The conversion of crystalline or

> powdery green or blue ores into tough red copper is a veritable transubstantiation. The change from solid to the liquid state and back again, controlled in casting, is hardly less startling (1942: 85).

We should not underestimate the significance of metamorphoses of moist earth in the fashioning of civilization. But as intimated by synthetic basalt of Mashkan-shapir, the solid-liquid-solid phase transition that Childe describes takes us beyond the domain of metamorphic geology and into the realms of the igneous. If the manipulation of sediment constitutes a significant anthropic engagement with the outer envelope of the Earth system, metallurgy, I argue, can be considered a capture of and elaboration upon the geophysical forces of the inner Earth: a literal enfolding of igneous processes into the vibrant core of the ancient city.

Just as the confluence of silt-laden rivers makes Mesopotamia an exceptional site for tapping fluvial sediments, so too are the convergent tectonic plates that shaped adjacent mountain ranges especially conducive to the extrusion of metal-rich magma (Yener 2000: 2, 80). While active orogeny or mountain-building pushed rock-layers upwards, seams of metallic ore were often exposed as ice, water and wind ground away overlying strata – the same erosion that fed sediment downstream to the alluvial plains. What began as trade between highland miner-metallurgists and lowland cultivators led to the relocation of metalworking operations in the growing alluvial population centres (Aitchison, 1960: 18). While there is long tradition – with roots in both ancient Roman and Chinese scholarship – of hitching the use of metals to human epochs, archaeometallurgists themselves have tended to recount more complicated, circuitous and entangled genealogies. Theodore Wertime is far from alone in acknowledging the debt of metalworking to pottery and envisioning all high-heat transmutations of matter as expressions of 'a single, complex pyrotechnic tradition' (1973: 676; see also Forbes, 1950: 290).

While metals may have initially insinuated themselves in ancient life as glittery novelties, most commentators agree that metallic objects came to serve as formidable instruments of urban-agrarian power – 'standards of utility for cutting, thrusting, digging and killing' (Wertime 1973: 680; see also Clark 2015). Recent scholarship, more interested in 'seeking pathways to ancient cognition and behavioral practices' than in the cut-and-thrust of ancient empire building, explores the contribution of metals to the emergence of generalized dispositions of measurement and valuation (Thornton and Roberts, 2008: 183). As Anna Michailidou (2010) proposes, metallic weights and tokens were pivotal in establishing a shared sense of value in the ancient world. Compact, durable and standardized, she adds, metal artifacts helped institute a sense of 'exactness' that facilitated the circulation of other objects through early civilizational networks.

While narratives of emergent valuation highlight the solidity of finished metallic objects, it is the prior solid-fluid-solid phase transitions executed by the artisan that draw us more fully into metallurgy's igneous dimension. The philosophical thematization of an artisanal creativity which tracks and extends transformational pathways intrinsic to the domain of matter itself is most often credited to Deleuze and Guattari, in their speculative engagement with metals and metalworking. Developing Gilbert Simondon's critique of a 'hylomorphic' model of technics, in which *lumpen*, unmotivated matter is lent form from an extraneous, vital source, Deleuze and Guattari (1987: 408-15) work up an early version of complexity theory to postulate an inorganic realm imbued with its own trajectories of self-organized transformation. For them, metals are construed as the probing edge of matter-energy's inherent exploratory drive, while the metallurgical arts epitomize the human ability to coax matter over immanent thresholds into alternative states.

Deleuze and Guattari take their cues from archaeometallurgical scholarship's long-standing fascination with metallic potentiality and those who actualized it. An abiding aim of this work is to understand how artisans spanning several continents came to acquire a working knowledge of smelting and alloying metallic ores (Forbes, 1950: 201). As metallurgist-historian Cyril Stanley Smith (1981: 325) notes, even as modern physics and chemistry began to decipher the deep compositional structure and basic processes in a range of heat-induced reactions, they came up against 'unanalyzable complexities' characteristic of the heterogeneous aggregates of materials with which metallurgists worked.

In the process of smelting or refining, ores are decomposed in order to extract base metals. This involves the application of heat and a chemical reducing agent or flux, as it is now understood, which both removes oxygen from a compound ore and separates metallic elements from mineral 'impurities'. Smelting and any later re-melting operations break down the relatively stable crystalline composition – the lattice structures that order most solids internally – followed, upon cooling, by recrystallization. Crystallization, the liquid to solid phase, is made up of two stages: nucleation and crystal growth (Diogo and Moura Ramos, 2006). Nucleation entails the initial formation of nuclei or 'seeds' around which crystals then aggregate or 'grow'. But this gets a lot more complicated when the metal in question is an alloy – a combination of two or more metallic elements – such as bronze, which is a mix of copper, tin and frequently, other metals and nonmetals. For with alloys, the phase transition from solid to liquid for each of the components occurs at different temperatures – making for extremely complex trajectories of change

(Capudean 2003).

Further complexities arise from what are now known to be 'imperfections' in the tightly-packed structure of metallic crystals. What gives metals their distinctive properties – lustre, ductility, conductivity – Smith notes, are the intercrystalline gaps or inconsistencies in their arrangement. Like the phase transitions of alloys, these irregularities defied scientific understanding until relatively recently. And yet, it is these unthinkable complexities that ancient metallurgists successfully negotiated in their daily work. As Smith recounts, albeit with a certain western bias, 'Egyptian, Minoan, Sumerian, Etruscan, and other early workers of metal made empirical use of most of the features of alloy constitution diagrams, and of hardening by solid solution, transformation, and cold working' (1960: 2). Like the physicochemical structure of metallic elements themselves – their characteristic mix of regularity and irregularity – he suggests, successive generations of metallurgists found the right blend of free play and more disciplined activity in order to attain a masterful degree of control over the requisite thermochemical reactions (Smith 1982: 49-54; see also Bennett, 2010: 58-60).

More than a tacit, improvisatory knowledge that preceded its modern technoscientific explication, we can view the metallurgical lineage as an anthropic capturing and elaboration of the phase transition undergone by that small proportion of rocky matter that is discharged from the inner Earth to its outer layers. From the perspective of planetary thought, the metalworker's heat-induced solid-liquid-solid trajectory reproduces the melting and decrystallization of the viscous crystalline rock of the mantle as it rises, only to harden or recrystallize when it stalls in subsurface fractures and chambers, or is extruded onto the planetary surface (Rothery, 2007: 21-31).

So too might we see these perceptive, embodied operations of the metallurgist as an enfolding and extension of the processes by which differential temperature and rates of crystallization in a magma chamber or other intrusion separate ore from non-ore minerals, resulting in the concentration of metallic ores (Drini et al, 2005). Just as the solid-liquid-solid transitioning of magma is made possible by the hardened lithic crust that largely but not entirely partitions the superheated inner Earth from its cooler surface envelope, so too, are pyrotechnic procedures of melting and resolidifying facilitated by the rigid wall of the furnace. Along with the technics of kindling and fluming extreme heat, this structural containment, inherited from the kitchen oven and the potter's kiln, permits metalworkers to install a potentially lethal igneous power near or within the habitable spaces of the urban environment (Clark, 2018). From there, the forged, cast, brazen, soldered, ground and polished outputs of the metal workshop would join the transformative flow of visual-tactile objects through the networks of the ancient world. As they continue to circulate through our own world.

Fluid-Rock Futures of the Planetary City

Urbanism, I have been arguing, is constitutively 'planetary' from the outset. If the phase transitions between solid and liquid that emerge as matter-energy negotiates a gradient field are one of the defining dynamics of the Earth (and other planets), then the city can be seen as a particularly intense and complex concentration of planetary morphological forces. Indeed, we might think of the conjunction of igneous and sedimentary interventions in emergent urban centres not merely as a decisive moment in human history, but as an intensification or even step-change in what our planet itself is capable doing (see Clark and Szerszynski 2021: 27-32). For although sedimentary and igneous processes join forces wherever magma intrudes or extrudes into sedimentary formations and whenever sedimentary rock is subducted into the Earth's mantle, it is only in the geosocial formation of the city that the igneous and sedimentary are coupled so tightly as to trigger an ongoing evolutionary radiation of novel behaviours, structures and assemblages.

From this igneous-sedimentary conjuncture, over the *longue durée*, come metal blades for cutting through soil, rock, fibre or flesh; agricultural surpluses administered and traded with the aid of metallic tokens, grain-fed armies equipped with metal weapons and armour; empires extended by firearms and gunships; metal-encased heat engines that mechanize the production of fibres sourced from distant alluvial plantations; motorized and metal-sheathed vehicles shifting agricultural produce around the globe in flows coordinated by messages transmitted through metal wires and cables; and catchment-altering mega-dams constructed by colossal metal machinery. If urbanism hinges upon an articulation of planetary processes from the outset, then it is hardly surprising that urbanization has come to manifest itself on a scale that is planetary in reach and impact.

Through physically engaging with locally manifest Earth processes, and in particular through acquisition of expertise in managing solid-fluid transitions, I have been arguing, 'the planetary' is enfolded into the lived experience of the city. But precisely what can be 'lived' is profoundly discontinuous, not just because of the way that geophysical dynamics exceed localization, but because of ongoing transformations in the social organization of the solid-fluid interface. With the ratcheting up of operations based on metallic ores and the outsourcing or offshoring of much of the manipulation of sediment, what were once familiar constituents of urban existence have tended to withdraw from everyday life – while they have concentrated in specialist zones or belts. In the case of metalworking, the workaday solid-fluid-solid transitions that once made

Smith, Schmidt, Ferraro, Demirci, Haddad, Kovač, Kowalski – and indeed, Lefebvre – into some of the commonest European and Middle Eastern surnames have largely been subsumed into large-scale mechanized operations distanced from metropolitan life. But as the excess of enfolded planetary forces increasingly rebounds at the global scale, the phase transitions associated with high heat technology have a disconcerting habit of reasserting themselves in daily life.

When wildfire sweeps through urban and periurban spaces – especially when it attains the magmatic intensities of a mega-fire – lifeworlds replete with metallic hardware are quickly reacquainted with the operations of heat-induced transmutation. Reflecting on recent Australian experience, historian Christine Hansen evokes a fire-seared suburban landscape: '(s)licks of metal that had been lawn mowers, car wheels, wheelbarrows, or bicycles had flowed into ditches and down driveways, resolidifying into pools of newly minted alloy' (2018: 228). Without overlooking the possible contribution of accidental urban fire to ancient pyrotechnic discoveries, we should not underestimate the cultural and cognitive impact of this sudden melting away of all that is most solid in the urban milieu.

Just as climate change is altering fire regimes, so too is it transforming the global hydrological cycle, with the result that sedimentary processes are impacting on existing urban spaces in new or intensified ways. Both routine urban rainwater runoff and more extreme hydrometeorological events recapitulate basic processes of fluid-induced disassembly of solid matter into smaller, more mobile particles. In the process, the organic-inorganic mix of non-anthropogenic sediment, and even the more varied effluvia of the ancient city tend to be far-surpassed by the heterogeneous discharges of the late-modern cityscape – which urban engineers inform us are likely to include 'heavy metals, biodegradable organic matter, organic micropollutants, pathogenic microorganisms, and nutrients, …. grind tire debris, vegetation (leaves and logs), animals (fecal contributions and dead bodies), fertilizers, and exhaust gas' (Zhang et al, 2013: 1).

The weathering of the multifarious solids of the contemporary built or altered environment reiterates the basic dynamics of their natural counterparts. As soon as sufficient shear stress is exerted by fluids, the phase transition between solid and suspended particulate is triggered, generating the considerably more-than-mud sediments of the present-day urban landscape. Relative to sediment morphology in general, urban hydro-engineers concede, little is known about the dynamic shift from solid to dissolved matter in the urban-industrial context (Zhang et al 2013: 1). So too must we consider the already occurring and intensifying inundation of coastal cities by sea level rise. 'Once drowned they will be removed from the realm of erosion into the realm of sedimentation', observes Zalasiewicz of the fate of low-lying urban spaces, as he proceeds to offer a detailed long-term trajectory of the numerous elements and compounds of which modern cities are composed (2008: 166; 165-172).

Lefebvre's (2014) 'Dissolving city, planetary metamorphosis' headline, we might say, now needs to be taken very literally indeed. Today, I am arguing, the originary urban experience of intervening in sedimentary and igneous geology needs to be thoroughly updated for Earth systems that are being propelled into novel operative modes or regimes. As if that were not enough, much of the sedimented matter that is being eroded by shifting and intensified hydrological processes bears the toxic residues of centuries or millennia of mineral extraction (Foulds et al, 2014). Thousands of years of turning the Earth's crust inside-out in pursuit of ores to fuel the metalworker's furnace has resulted in extensive accumulation of waste rock 'tailings' from mining and quarrying. As hydrological regimes undergo reorganization, these extractive topographies – including many that were abandoned centuries or millennia ago – are being subjected to fluvial decomposition, bringing heavy metals and other toxic elements into circulation (Foulds et al, 2014). So too are these radically destratified landscapes, along with their fossil-fuel extractive counterparts, vulnerable to the impacts of shifting and intensifying fire regimes.

To approach anything remotely like urban liveability under conditions of Earth system upheaval will require not just a reconsideration of the metaphorically 'fluid' relationship between the city and its surrounds, but a full accounting for the complex, creeping and cryptic interchanges between the solidities and fluidities that compose the very substance of the urban. As megafires re-smelt the stuff of suburbia and as floodwaters or rising seas deliquesce entire urban landscapes, we will be pressured to acquire new skills not only for safeguarding 'planetary boundaries' but also for working with and through matter undergoing phase transitions. Which is to say, we must attune ourselves to physical processes that are themselves sorting, coursing, morphing, probing.

If there's any consolation, it is that 'civilization' brought this predicament upon itself precisely by doing all these things, and often doing them astonishingly well. Much of the foundation of urban life rests on collective aptitudes for capturing and elaborating upon our planet's own structuring solid-fluid phase transitions, an insight that is clearest at the formative moments of certain cities – which was itself a time of considerable climatic instability (Clark, 2020). The resurgent planetary thought I have been sketching out would have us see cities as being crafted, in part, by skilled collective acts delving into and prising open transitional processes generated by a far-from-equilibrium planetary body. If we are to reorganize our urban spaces in response to the current reorganization of the Earth system, or at least to manage their acquiescence to insurmountable change, we would do well to dwell upon our long, impressive history of guiding matter across solid-fluid thresholds.

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