READING CLAY: THE TEMPORAL AND TRANSFORMATIVE POTENTIAL OF CLAY IN CONTEMPORARY SCIENTIFIC PRACTICE

INTRODUCTION

There has been increasing interest in clay and soils, and a call to take materials into account in exploring the agentic and relation nature of human and more-than-human worlds (e.g. Ingold, 2007; Landa and Feller, 2010; Bennett, 2010; Barad, 2003; Haraway, 2008; Boivin and Owoc, 2004; Drazin and Kuchler, 2015). While anthropologists, geographers and archaeologists have extensively theorised practices around clay through work on geophagy (e.g. Henry and Kwong, 2003), pots (e.g. Gosselain, 1999), figurines (e.g. Weismantel and Meskell, 2014), and body painting (García and de Ágredos Pascual, 2019), this extant research predominantly focuses on 'lay' uses of clay most often in the global south where clay is more commonly used in domestic life. As such, clay has been considered 'exotic' (e.g. see Jamie and Sharples, 2020) in the Western gaze and paradoxically 'too natural to be culturally acceptable' (Henry and Kwong, 2003:362). Since the re-turn to materialism clay has come under scrutiny across academic disciplines with a focus on different eras, and traditional and contemporary societies across both the global south and north (Boivin, 2008). Clay has been a focus of recent research on art, craft and leisure including gardening and pottery with academic work exploring the co-constitution of people and things (e.g. Landa and Feller, 2010; Boivin, 2008). However, explorations of clay in social science research has rarely focused on contemporary 'Western' laboratory-based 'hard science' which does not usually deal with the human elements of clay (i.e. how clay is/has been used by humans over time and in diverse contexts) so much as the fundamental chemical properties of the material. This lack of interest occurs despite the relatively rapid growth of 'clay sciences' (Beragaya and Lagaly, 2006) with clay increasingly being harnessed in scientific study to transform multiple aspects of human life including health (e.g. Williams, 2019; Williams and Haydel, 2010; Williams et al., 2004), pollution control (Churchman et al., 2006), environmental sustainability (Dempster et al., 2012) and for industrial applications (Harvey and Lagaly, 2013).

Specifically, we explore how clay is ‘read’ and works as a ‘partner’ (see Salisbury, 2012) in contemporary science. Our focus is on understanding *‘what and how can clay become?’* from the perspectives of a multidisciplinary group of scientists who work with clay, whilst also being alert to culturally located and past knowledges of clay. We reveal how epistemological and ontological understandings of clay inform how these scientists work upon clay to potentially transform social life. In asking scientists *‘what and how can clay become?’* we are not claiming to explore all of its scientific meanings, nor are we suggesting that science has a definitive answer, or that scientists’ interpretation of clay’s materiality and potential is any more ‘correct’ or valued than ‘lay’ understandings. Moreover, we are keen to avoid entrenching a rigid, false dichotomy between lab-based scientific knowledge about clay, and knowledges which emerge from other disciplines such as geography and archaeology. We recognise that disciplines such as these represent an intellectual space where the ‘hard’ and social sciences meet around a shared interest in clay. However, we intend to contribute to understandings of granular matter by exploring lab-based scientific practice as one space in which clay is made sense of and science as one ‘gaze’ through which clay, as a ‘thing itself’, is constructed.

To do so, we begin with a case study using qualitative interviews with six international scientists for whom clay is an integral focus of their research. The scientists worked across the fields of archaeology, chemistry, geology, biology and civil engineering, and have diverse foci in working with clay. We intend this paper to further focus sociological attention on the granularity of clay across diverse settings– lay, expert, global north, global south, past, and present. We also aim to contribute to the process of building knowledge on relational approaches to granular matter and specifically science and clay in shaping contemporary social worlds.

The article begins by analysing clay as socio-cultural matter that comes to be known through specific ontologies. We then provide an overview of the research design and findings which explore established practices of reading clay; clay as informational and clay mediated via science to potentially transform environmental and human health. The findings bring to the fore how clay comes into being, that is, how it becomes known, interpreted and transformed by scientists in their ‘reading of clay’ to produce social, economic, historical, cultural and environmental knowledge and applications.

CLAY AS SOCIO-CULTURAL MATTER

There is a diverse literature across ‘natural’ sciences, humanities and social sciences including for example, anthropology, archaeology, geology, social geography, soil science, art history and art examining the potential of clay and cultural and social practices associated with clay. It is beyond the scope of this article to delve into the breadth of disciplinary and multi-disciplinary contextualisations and understandings of clay. We focus here on significant readings of clay in archaeological, anthropological and ‘clay minerals studies’ to provide examples of clay as socio-cultural matter to explore how through these meanings knowledges about clay in the social worlds emerge.

Skibo (2013:3) suggests that the study of clay has been ‘ubiquitously archaeological’. Archaeologists have, as just some examples, highlighted the extensive use of ochre in the Palaeolithic period and beyond (e.g. Taçon, 2004) and the moulding, shaping and sculpting of figurines as depictions of contemporaneous social relations and roles (Hamilton, 2000). The placement, production and use of pots in ancient civilisations has been extensively studied in order to understand settlements, communication and social relations among households and communities, questions of social identity and belonging, and functionality for example in agricultural and food, water, milk storage, preservation and consumption practices (e.g. Schiffer and Skibo, 1997; Jones, 2004; Schiffer, 2004; Badreshany, 2016). Archaeological work also brings to light the importance of clay as a material for building cities of the ancient world (Stevanovic, 1997). The clay which constitutes 'things' like buildings or pots has also increasingly been analysed to identify for example, volume, organic-residue, fabric, thickness of walls and so on to distinguish the variability and differences that constitute various pots (see Jones, 2004; Schiffer and Skibo, 1987; Skibo, 1992). As Skibo (2013:2) suggests analysis of the 'stuff' of clay provides a medium from which to analyse technical choices and 'technical properties', and their implied and applied function. Significantly, there is a body of archaeology study that uses scientific techniques from geology, namely petrography, to examine using various microscopes the substance of clays to determine temporal periods, infer and also discover (e.g. through residue etc) utilisation of clay materials. The method of petrography has been used by scholars like Skibo (2013) to also understand cultural practices and social arrangements associated with clay's use and transformation (e.g. Jones, 2004; Skibo, 2013). Thus, in this way clay products or fragments are 'objects' of study and 'subjects' of culture (Jones, 2004).

Anthropologists have focused on traditional and contemporary uses of clay in the global south in cosmetic and beauty products (Matike et al., 2010); to make jewelry and coins (Ferraro, 2019); the cultural-locatedness of eating clay within everyday nutritional practices (Henry and Kwong, 2003); and the symbolic and ritualistic association of pottery with transitory states like birth and death (Gosselain, 1999). Anthropologists have also explored customs associated with body painting including for artistic, decorative and celebratory purposes, to appear attractive and to prevent poor physical and emotional health (Fayers-

Kerr, 2019). Fayers-Kerr (2019) brings attention to relationality of clay and bodies and in particular the notion of becoming with clay drawing on the theoretical work of Karen Barad (2007) and Donna Haraway (2008). She uses ‘intra-action’ (Barad, 2003) to explore how bodies come into being through and with multiple ‘matter’. In this way the becoming of the subject is not external to the object or caused by it but emerges relationally between ‘object’ and ‘subject’. For example, for the Mun black clay is used for ancestral clay-pits and as clay in the pits becomes differently constituted it is sourced to retain ancestral connection and wellbeing (Fayers-Kerr, 2019).

Bergaya and Lagaly (2006:1) suggest that ‘if the general knowledge and usage of clay have ancient roots, the scientific study of clay (i.e. ‘clay science’) is a relatively recent discipline, dating back only to the mid-1930s, following the emergence and general acceptance of the ‘clay mineral concept’. For Bergaya and Lagaly ‘science’ clearly is bounded and conferred upon the natural sciences. Hence, the study of clay minerals is arbitrarily constituted as beginning with the discovery of X-ray diffraction in the 1920s which allowed the visualization and identification of clay minerals (Moore and Reynolds, 1997). Within this discipline and further development of technologies, clay research has further flourished enabling the identification of clay minerals’ characteristics and potential for social and industrial application (Bergaya and Lagaly, 2006). Indeed, as Bergaya and Lagaly (2006:16) point out ‘clay research is being actively pursued by many people…[and with] The great variety of physical, chemical and thermal treatments…used to modify clays and clay minerals [there is] unlimited scope for future applications’.

This ascendency of clay into the gaze and physical spaces of laboratory science necessarily draws attention to its granular materiality. Scientists have classified and categorised clays and their constituent minerals according to understandings of their elemental, structural and mineralogical composition (Bergaya and Lagaly, 2006). However, what constitutes clay has diverse, and sometimes controversial, meanings among scientists and scientific disciplines including geologists, agronomists and engineers (Guggenheim and Martin, 1995). Commonly, clay minerals are understood as particles of less than 2 µm in diameter, however, others have argued that clay is determined by whether it is a phyllosilicate; that is a material made up of one or two types of crystalline structures at least at the molecular level (Brigatti et al., 2006).

The ontological distinction made between clay and clay minerals is important for a diverse array of scientists from wide-ranging disciplines who characterise their origins and composition, harness their properties and adapt them for industrial and medical applications (Wesley, 2014; Williams and Haydel, 2010; Aguzzi et al., 2016). However, for the purposes of this article, these distinctions are not critical and throughout we refer to 'clay' as an overarching term incorporating both clay and clay minerals.

In this paper we are interested in clay as a material which is both transformed by a particular set of scientific practices and is understood to transform other materials external to it. This notion of clay as transformed/transformative runs deep within the existing literature as clay has a history of being transformed to create new cultural products which in turn may transform other things. At a fundamental level, the archaeological and anthropological gaze has focused on clay which has already been transformed into new materialities such as pots, figurines, coins, bricks, paint, or food. This transformation process from 'raw' clay to socially meaningful artefacts can be seen in the case of geophagy where preparation of clay for eating 'bring it into culture', transforming it from inert earth into an edible substance (Henry and

Cring, 2013:181). Barley (1994:99) similarly notes in the case of pottery that 'potting involves a number of changes. It takes formless matter and shapes it. It transforms, through the operation of heat, from wet to dry, soft to hard, raw to cooked, natural to cultural, impure to pure'. Levi Strauss (1985) similarly notes that potting involves process of alchemy, transformation and entanglements of different materials – water, fire and earth. These kinds of transformations of clay are both physical and symbolic. In the case of pottery, while raw clay is *physically* transformed into the new materiality of pots, these pots stand as a *symbolic* metaphor for key transformative and transitory moments in the lifecourse (Gosselain, 1999:214).

This extant literature on clay shows us that clay's material 'thingness' - its colours, its malleability, its ease of extraction, its absorptive properties - has shaped and transformed human civilisations, relations, and the course of human cultural and biological evolution. Yet, as Weismantel and Meskell (2014) argue, the substance of clay itself has not been readily subject to close analysis. They show that while clay *products* (in their case figurines and effigies) are extensively theorised across archaeology and anthropology, these products 'embody particular forms of engagement with the material world, and have material effects on that world through their social histories of production, use, exchange, and discard' (Weismantel and Meskell, 2014:234). This relative neglect of clay's materiality is reflective of a wider approach in social sciences where materiality is frequently taken as a set of practices, objects, and mobilities, rather than *material substances* themselves. For Salisbury, for example, 'soil too frequently plays the role of overburden, or the stuff holding the more important things, like stones and bones' (Salisbury, 2012:23). As such, archaeologists have tended to overlook 'the influence of the materiality of soil on identity, place or memory' (Salisbury, 2012:24). Such neglect of substances occurs outside of archaeology too (Anderson et al., 2006).

This is not to say that granular material has completely escaped attention. It has increasingly been the subject of study in archaeology and anthropology with the re-turn to martieralism. In addition, social and cultural geographers have also focused on soils in relation to environmental degradation and agricultural production (e.g. Lichtfouse, 2010; Robinson, 2004), sand and its entanglements within political economies and tourism (e.g. Kothari and Arnall, 2017) and soil as deeply embedded in the constitution of politics regarding place and identity (Salazar et al., 2020). Here we are focused on what and how clay becomes meaningful through the gaze of laboratory-based science, as an object of scientific transformation.

RESEARCH DESIGN

A qualitative approach using semi-structured interviews was employed to understand scientific interpretations and practices associated with clay. Our curiosity in this area arose from our participation in a collaborative interdisciplinary network of researchers focused on potential health and environmental uses of clay. This network comprised twelve academic scientists working across diverse laboratory-based disciplines, alongside four social scientists. The laboratory-based scientists in this network were concerned with uncovering the geochemistry and microbiological profiles and potential applications of specific clays. Alongside this biomedical focus, our social science research explored the ‘social life of clay’, specifically its uses in diverse cultural contexts and its ascendency as a contemporary scientific artefact.

Given the coalescence of diverse methods and epistemologies in this network, we wanted to understand how our science collaborators made sense of clay. Our focus on materiality represented such an ‘intersection’ (Gerson, 1983) where diverse epistemologies coalesced around the empirical focus on clay. To explore clay’s materiality in scientific practice, we temporarily relinquished our position as collaborators to undertake interviews with a sub-set of our scientific colleagues in a traditional researcher/participant dynamic. This enabled us to occupy a position of 'naivety' through which we could broach fundamental questions like *'what and how can clay become?'*.

Participants and Data Collection

Six scientists were recruited from our collaborative network who were working closest with clay as an empirical artefact and had the clearest entanglements with clay's materiality. We did not interview an anthropologist because the network's anthropologist did not conduct laboratory-based experimental work on clay. Table 1 describes the participants' disciplinary backgrounds and research with clay materials. The participants' disciplines and research foci have been simplified as many participants work across, and at the interface of, different disciplinary areas and have multiple intersecting research interests in clay. For example, when asked to describe his disciplinary background, Participant 2 answered: 'Geologist. I also describe myself as geobiologist, palaeontologist, palaeobiologist, astrophysicist, geomicrobiologist – it depends on context'.

Table 1: Participant Disciplinary Profile

Participant Pseudonym	Disciplinary Area	Empirical Interest in Clay
Participant 1	Earth Sciences	Pollutants. Clay’s role in water purification. Life on early planet Earth.
Participant 2	Geology	Clay’s role in the preservation of fossils to enable the study of microorganisms. Life on early planet Earth.
Participant 3	Geology / Microbiology	Antibacterial mechanisms of clay. Clay mineralogy.
Participant 4	Earth Sciences	Clay as a water purification material.
Participant 5	Geology / Mineralogy	Composition of clay minerals. Antibacterial mechanisms of clay.
Participant 6	Archaeology	Clay pots as a lens to ancient societies and economies.

Participants were recruited via email and all agreed to be interviewed. Individual one-to-one interviews were conducted face-to-face or by telephone in November and December 2019 and typically lasted 30-45 minutes. The semi-structured interviews covered participants’ academic trajectory, current and future clay-focused research, and reflections on the materiality and nature of clay.

Data Analysis

Interviews were transcribed and thematically analysed using Braun and Clarke's (2013) six step process. First, we familiarized ourselves with the data through repeated reading and note-taking before moving on to generating an initial coding framework which both labelled the specific understandings of clay within individual disciplinary cases (i.e. participants) and identified synergies across the dataset. These codes were then grouped into thematic categories in line with our focus on materiality, clay-as-artefact, and human and more-than-human relations. From this grouping stage, we identified the notion of transformation whereby, through participants' 'readings' of clay, the material was understood as potentially transformative in multiple 'directions' and at different 'levels' of socio-material life. We then interrogated the data further to identify, define and refine the specificities of this transformative potential.

Braun and Clarke (2019:594) suggest that themes arise as interpretive stories. In analysing the data we bore in mind the theoretical framings of materiality, transformation and the existence of the 'more-than-human' in socio-natural entanglements; the specificities of these in relation to clay became apparent and vivid through the iterative process of induction and deduction from data to theory.

ESTABLISHED PRACTICES OF READING CLAY

Although our participants work in a variety of academic disciplines, there are several commonalities in their practices with clay; a key one is what we describe as 'reading' clay. For all our participants, reading clay enables description and standardisation of clay materials. This reading process is ontological; reading clay as 'texts' brings clay materials into being, making them knowable and imbuing them with potential for a variety of uses and applications depending on their description and classification (see Chakravartty, 2017).

Participant 4 commented that the start of any research on clay must begin with this ontological reading process through which researchers are able to establish what clay *is*:

> You need to know the characteristics, what are the elements of the clay and how effective it is.

Reading clay in this way involves collaboration between researchers, technologies, clays, and existing schema to produce knowledge about clays as static, inert materials such as their structure, size, shape, and chemical composition. Participant 1 described this human and non-human co-production in the reading process:

> We use Wyoming bentonite, kaolinites from Georgia in the USA. The US Clay Mineral Society actually keeps a library of clays which have been characterised… We use chemical force microscopy or contact angle measurements and we are increasingly using biological imaging techniques like confocal fluorescence microscopy.

Participant 2 showed how reading produces visual knowledge about the structure of clays which feeds into characterisation processes:

> We can refer to phyllosilicate minerals as clays, these are minerals that have a structure that is like stacked pages in a book, on a microscopic scale those are the phyllosilicates.

For Participant 4, reading clays was linked to their provenance, and localised applications and uses:

> The most important thing for me is to think about what the clay is. We use the local material, so we need to know the properties to just know what the clay is.

As well as being ontologically important by defining what clays *are,* reading also represents a key epistemological moment in clay science. As such, reading organises how different clays will be worked upon, what kinds of questions will be asked of them, and by whom. Participant 4 commented, ‘People look [at clays] from different angles’ depending upon disciplinary epistemologies.

For Smith (2008:1, original emphasis), this ontological and epistemological work of reading and describing materials has become ‘*a part of science’* and a key way through which data is generated, organised and analysed. Smith (2008:7) argues that specific scientific ontologies, such as descriptions and classifications of clay, are formed through the gradual expansion of a ‘consensus core’ of ‘hypotheses which began as problematic but have withstood attempts to refute them empirically’, and the testing of new materials, theories and applications against these ontologies. This can be seen in the case of clay where the ‘consensus core’ consists of established knowledge about the ontology of particular types of clays and their uses. For example, clay’s absorbency is a well-established scientific premise (ontology) which then directs other work such as its ability to preserve fossils or neutralise harmful pathogens in water (epistemology).

This ontology does not just emerge from contemporary scientific readings, epistemologies and techniques but is also rooted in lay knowledge spanning time and space. Several participants referred to cosmetic practices involving clay and geophagy as somewhat logical when understood against the consensus that clay is absorptive and has some antibacterial properties. For example, Participant 3 commented: ‘A lot of people eat clays basically to resolve problems with digestion. They eat clays to absorb water and toxins from their stomach.’ Participants 4 and 5 pointed out that lay practices with clay (including but not limited to geophagy) emerge from lay knowledge in the global south and ancient cultures:

> Participant 5: Old people who live in [our] village use clay for cosmetic reasons. My grandmother washed her clothes and hair with clay.

> Participant 4: They have their own old, Egyptian way of making perfume with no chemicals, so he told me that they put this extract in a clay pot and leave it in the desert for one or two months. After that they take it back…[as] it changes in quality. In the museum, I saw this inscription. It was in hieroglyphics and [the tour guide] said this is still the way that they do it nowadays.

In other words, contemporary scientific readings of clay and the ontologies that they produce are mediated by knowledge and language that ‘pre-exist us’ (Belsey, 2013:167).

Paradoxically, while reading aims to produce somewhat standardised knowledge about clays (a ‘consensus core’ or ontology), it also positions clay as an ambiguous and liminal material. For example, although Participant 1 used the US Clay Mineral Society library of clays as a standardised control in his descriptions, he also went on to highlight the challenges of developing a standardised characterisation of clay which is a ‘fairly dynamic structure’.

However, how clay is understood to be greater than the sum of its parts or what chemically constitutes clay. Reading clay imbues it with agency and the potential to *do* things, particularly to interact with and transform other material forms. Clay in this way, is following Barad (2003) not simply interactive but 'intra-active' coming into being with multiple matter and 'becoming with' through transforming alongside other matter (Haraway, 2008). This relationality is multidirectional whereby clay material can itself be transformed into new materialities or functionalities (what we might understand as 'clay as transformed') or can be used to transform other materials (what we might understand as 'clay as transformative').

CLAY AS INFORMATIONAL

Commonly, the scientists participating in our study read clay as a temporal medium. Like other granular matter, such as sand, clay 'connects the elemental to the global, and the distant past to the present' (Brigstocke, 2016, cited in Kothari and Arnall, 2020:305). At the most fundamental level clay is read as critical to evolution. It 'play[s] an important role in the origin of life' and 'if organic matter is not oxidised and the oxygen in the atmosphere is high enough plant, animal and human life is possible' (Participant 3). Participant 1 explained:

> …we look at how clay might have been an incubator for the life of the early earth… there is an idea [by Kent Smith] that clays were literally the original unit of life on earth. The idea around it has waxed and waned but I don't think anyone has every experimentally come up with looking at the ways of inheritance that he was talking about.

Participant 2 also explained:

> Microbial life…has a role in the evolution of our planet…microbes play a role both in breaking down and decaying organic matter but also in facilitating the production of minerals that preserve fossils. So, clay is also an information medium. It is a gesture of the environment in which microbes live. It is a substance in which they are affected by and which they affect with their own activity.

The above quotations reveal several points about the reading of clay. First, critically clay minerals are 'catalysts' whether it be in the origin of life according to Bernal and Fankuchen's proposition (1941) or 'for the formation of biopolymers of the first life in aqueous environment' (Brack, 2006:518). Secondly, diverse clay minerals are an agentic relational medium as they interact with microbes enabling transformations. In relation to microbes, Dong et al. (2009:11) have argued that, 'multiple clay minerals such as dioctahedral smectite-illite series, palygorskite, chlorite and their various mixtures in natural soils and sediments…are reducible by microorganisms under various conditions. The rate and extent of bioreduction depends on many experimental factors, such as the type of microorganisms and clay minerals, solution chemistry and temperature'. Participant 3 explained that:

> Microbes are primitive enough that they can change the structure and chemistry of clay…Some microbes can oxidise ferric back to ferrous even without oxygen. Oxygen can do this too and so microbes can change the swelling property…microbes are the major force to change clay properties.

In this reading, clay has a fundamental role in transforming the earth from inert and lifeless to a biodiverse environment. Moreover, for some of the scientists participating in this study 'clay is an information medium' which through weathering can be created and transformed and thereby enable the reading of past climatic conditions and the preservation of fossils. Participant 2 explained that the size of clay particles provides an encasement for fossils:

> If a mineral is made of very small particles then if you wrap it around a carcass it is going to be able to fill in smaller spaces and more faithfully replicate the fine details. Smaller particles in your sediment can mean that you have a higher resolution of preservation than if you had coarser particles. Smaller mineral particles result in the sediment excluding more water overall sealing off [organic remains] and prevent[ing] interact[ion] with agents of decay.

Reminding us of clay's ambiguity, Participant 2 also clarified that 'different clay minerals are likely to differ in their capacity to preserve fossils'. McMahon et al. (2016:869) argue that clay minerals provide a 'higher quality of organic tissue preservation…However, clay-bacterial interactions are highly specific with respect to both clay mineral composition and bacterial strain'. Fossilisation is rare and most of the species that existed will not be recorded in fossil records (Parry et al., 2018). Fossils, however, are not 'perfect snapshots' of extinct organisms (Parry et al., 2018:2) as soft-bodied fossils will alter and change due to weathering, self-digestion through enzymes and microbial decay. Reading the fossil record requires a reading of what characteristics are missing and what might have been destroyed during excavation. Both the constitution of fossils, how they might change, when and where they are found and how they are interpreted are deeply implicated in time and epistemologies. Geological and biological knowledges are required to interpret the preservational context as well as the actual fossil (Parry et al., 2018). Geological time, which is somewhat contestable and continually being refined (Westerhold, Rohl and Laskar, 2012) informs the location of fossils in geological strata with respect to time (e.g. Eons: Hadean, Archaen, Proterozoic and Phanerozoic, which are further divided into eras, periods, epochs and ages).

Across geological and human histories tied up with clay, biological processes inform what is preserved, how and when, for example, ‘Factors other than decay can result in counterintuitive results (such as the preservation of muscle not cuticle)’ (Parry et al., 2018:12). These epistemological knowledges use the past as a referential position for present analysis, with contemporary science analysing how clays are transformative and open to multiple temporalities interacting with environmental, human and more-than-human entanglements.

PARTNERING CLAY: TRANSFORMING HUMAN AND ENVIRONMENTAL HEALTH

The reading of clay by scientists in this study as an interactive, agentic and relational materiality shapes how they ‘partner’ with clay to produce products that are potentially socially transformative. In this study scientists were particularly interested in the possibilities of working on and with clay to transform medicine and health, and environmental degradation.

Transforming health and medicine

The matter of clay is important in contemporary science as Western knowledges have become increasingly limited in relation to the efficacy of antibiotic treatments. Prompted by the inappropriate and overuse of antibiotics in human and veterinary medicine since the mid-twentieth century, and coupled with the dearth of new drugs being brought to the market, antibiotic resistance poses a significant global public health problem (World Health

Organization, 2014). Against this backdrop, biomedical researchers are turning to increasingly innovative materials to identify new antibiotic agents including natural materials for their therapeutic potential. A major site of study for our participants is the potential application of clay as an antibacterial agent. Participants explained that not all clays are antibacterial and that as clay is not a static agent, microbial relationality determines whether clays may have antibacterial potential. Participant 5 explained how iron rich clay interacts with bacteria:

> The bacterium eats iron in the clay and the clay changes and transforms to other minerals…iron is destroyed…But [with] antibacterial clays then clay will interact with bacteria and kill bacteria and some elements will leach from clays and destroy the bacteria at the same time the chemical composition of bacteria can be changed. Sometimes if they don't interact nothing changes.

As science 'revert[s] to "nature" for answers' (Thomford et al., 2018:1) but also to knowledges located in the global south to manage antibiotic resistance, clay has begun to take centre stage for its potential in antimicrobial therapy. Participant 5 explained historical and culturally located medicinal uses of clay:

> We know there are a lot of benefits from past times. People…[still ingest] clay…[you need to know] where it is located and to collect it, clay has very small particles and it is best to mix it with water and this separates as the surface area is large and that separates elements.

Drawing on insights from the study of animals Participant 1 suggested that these knowledges could drive future learnings, he explains:

> …many animals undertake geophagy, but the reasons are not fully understood. There is the notion that they can remove toxins from the gut, or they can aid a digestive process…is a really interesting area to take forward.

Whilst clay and its antibacterial potential have a long history (Hosseinkhani et al., 2017), it is only recently that Western biomedicine has begun interrogating clay matter for its potential active role in pharmaceuticals (clay has been used as an excipient in Western biomedicine for a considerable period but not as an active ingredient). X highlight that clay's potential to transform bacteria is bringing clay 'from the margins to the mainstream' of biomedical research (e.g. Williams et al., 2004; Williams and Haydel, 2010; Williams, 2019). The time lapse between cultural knowledge about clay's healing potentials and also knowledge drawn from the behaviour of other species to present day investigation speaks to what matter has been privileged, interpreted and remembered in science (Rose and Tolia-Kelly, 2012; X).

Transforming environmental pollutants

Participants were also exploring the possibilities of clay as an agent that can transform water or soil for human and environmental wellbeing. Participant 4's research centred on removing toxic agents from drinking water to decrease child mortality. He explained:

> [Clay] is not just transforming water but also has the potential to affect mortality. That is something we can't study in the short-term, but we are sure that this could be

> helpful in transforming water for drinking. It [a clay water pot] has a volume of five litres which could be used for hours for a family of eight…In Afghanistan, of 5,000 people 1,500 will die before the age of five because of the problems water causes so its quality matters…

Anticipatory social change for this participant stems from an ontological interpretation of historical and cultural processes of water purification elucidated in his comment of surety about water filtration and health. It is a recognition of an epistemological commitment, that is, understanding 'how far empirical results can be plausibly extended to give us knowledge' (Chakravartty, 2017:xiii). It is also a recognition of landscapes of knowledge (Livingstone, 2010) in that the notion of returning to clay stems from past culturally and geographically located practices. He explained:

> I was recently in Egypt and I was looking at the museums and the early age of the Egyptians were using clays to store water. The same thing was happening in Afghanistan. People were making clay pots and they still do it. It is something people know about, but we want to change this perception that it [was] only used for [previous] generations.

In the above example the museum becomes a critical spatial site of scientific knowledge, providing in-depth information about clay and its interconnectedness to cultural and social systems and the development of economies (e.g. Hodder, 2011).

This temporal reading of clay indicates how different epistemic scientific agents in the past and present arrive at similar inferences (Chakravartty, 2017). These inferences reflect shifting social and economic uses of clay occurring alongside shifts in scientific knowledge as plastic bottles came into production post 1950s for storing water and other consumable drinks. Plastic bottles were manufactured to replace glass because they were lightweight and cheap. The shift from glass to plastic is an exemplar of science being deeply intertwined with economic and cultural systems. As Participant 4 suggested 'we want to change perception' that clay was only used in previous generations suggesting that consumers may see clay for the creation of vessels as perhaps old fashioned, clunky and less relevant to contemporary lifestyles. Further, the temporal production of a consumable object also sits alongside a temporal scientific epistemic commitment to discover and construct a more enhanced product; in the case of PET plastic bottles (post 1970s), a material that is more easily recycled and therefore has greater degradability. The limits to this epistemic function are to produce, as Participant 4 suggests, a new commitment to return to clay. Clay is being studied to discover its social possibilities for filtering and cleaning water but also for reducing waste and degradation to land and waterways from overuse and the disposability of plastic bottles.

More widely, different varieties of clay have multiple applications related to environmental transformation and reduction of pollutants. Scientists also discussed the possible uses of clays to remove toxins from soil. Participant 1 explained that:

> …chemical[ly] [clay] interacts with things…so in areas where you might have nuclear species leaking into the environment, they might be used to contain nuclear waste…

The ontology of particular clays like bentonite and bentonite/sand mixtures are less porous in a saturated state and are able, through diffusion, to procure waste. As bentonite 'self-seals' it provides a barrier to prevent waste leaching into the environment (Gatabin et al., 2016). The dual agency of clay as a living, moving materiality that according to Participant 1 'moves around quite a lot…as they take up biomolecules into their interior' and scientific agency through discovery and testing, brings forth new social applications of clay. He explained this agentic duality:

> If we are working on things to do with oil reservoir stability then they will treat it with different salt solutions or different oil model solutions and then we will look at how we change the conditions of the clay, to change a property called weightability which is the relative affinity of the surface for one liquid or another. When you are trying to get oil out of a reservoir, you want to get oil out of a wet surface to a water wet [surface]…what we are trying to see is whether we can induce this change from clay preferring oil to preferring water. Sometimes it's a function of the clay surface and sometimes it's a function of the oil itself.

Participants 1 and 4 ontologically read clay as a material entangled in more-than-human and human agencies. There is an implicit understanding that science is working toward rectifying the impact of human and economic forces on the environment. Their epistemic stances are consciously drawn from a political situatedness that positions their science as responding and transforming the environment through the medium of clay. This relational nature between scientific learning, political, economic and social life has been well acknowledged (e.g. Haraway, 1988; Harding, 1986). In terms of granular geographies, Kothari and Arnall (2020) discuss the study of climate change, ecology and sand erosion and how these knowledges inform the transportation and marketisation of sand to coastal 'idylls' for tourism. In relation to clay, there is vast potential to explore how clay is temporally entangled and shapes political, economic, and social life.

CONCLUDING REMARKS

This paper argues in favour of a focus on the temporalities and granular materiality of clay, and its entanglement within human and more-than-human networks, particularly its transformative potential within scientific knowledge and practice. While clay has been fairly extensively explored in contexts in the global south, its material importance in 'Western' science has largely been overlooked by social scientists, despite the widespread use of clay across diverse research disciplines and its promises of future functionality. To attend to this, we have drawn on a small-scale research study with six clay scientists to provide an entry point for thinking about clay as a socio-cultural material and its movement across diverse spaces from south to north, margins to the mainstream. We have suggested that for all participants, clay is read as relational in a multitude of ways through its interactions with microbes, elements, and human interaction. Indeed, when asked how is clay transformative one of our scientists remarked, 'where do you start with that?'

In making this argument, we return to the question *'what and how can clay become?'* In asking this in relation to scientific practice specifically, we have identified the ontological and epistemological process of 'reading' clay as bringing it into being as a potentially transformative material artefact. This transformative potential spans different 'levels' of change, from molecular-level alterations of chemical composition and structure, to global changes in public health. This reading also locates clay within particular temporal and spatial modes, and as holding multiscalar promises of social and environmental transformation. 'Reading' clay material, then, involves a process of not just simple description and characterisation but also constructing clay as a promising artefact. Additionally, we have highlighted the agentic materiality of clay as it has the potential to transform and be transformed – for example, raw clay may be transformed into a pot (a new materiality) which is then used for collecting, storing and transforming polluted water into water which is safe to drink. Laboratory science enables new dialogues about different clays and their molecular and microbial agency in specific settings, contributing to knowledges about how clay comes into being in variegated ways. Equally, disciplines like anthropology and archaeology provide unique insights about how temporal and spatial practices and knowledge of clay lend laboratory science with contemporary opportunities from which to imagine and experiment with the transformative potential of clay. Whilst there is multidisciplinarity within 'clay sciences', anthropology and archaeology we suggest there is potential for interdisciplinary work across these fields to explore what clay may become. Ingold's (2103) work on thinking with multiple disciplines and specifically anthropology, art, archaeology and architecture is an interesting foundation for the study of clay which may be extended to include 'clay sciences'.

However, we are conscious not to overstate the transformative 'power' of clay as, in several cases, clay was described by participants as being, or becoming, untransformative in the ways we have described here. For example, one participant noted that, 'once clays reach equilibrium with their natural environment then change doesn't occur beyond that point' (Participant 1). We are also cautious of representing clay as the only medium through which health and environmental transformation is taking place. In the case of health, for example, while clay has been positioned as a potential active ingredient in a new generation of antimicrobial products (see Williams, 2019), other natural antimicrobials like honey (McLoone et al., 2016) are also increasingly being explored as a solution to antimicrobial resistance. Moreover, the post-colonial politics and power, and interwovenness of race, ethnicity, culture and diverse knowledge systems that we have pointed to here are not exceptional to the case of clay. The movement of clay into the gaze of 'Western' science and the increased valuation of clay as a material artefact that accompanies this is reminiscent of similar stories involving plant materials (see Hayden, 2003).

Although we are urging caution about overstating the exceptionalism of clay as a material artefact, there are other ways that clay *is* unique and worthy of further social science investigation. There are few other materials which are as central to everyday life across the globe as clay and we are surrounded by and in constant contact with clay like no other material. As the sustainability agenda gains increased traction, it is likely that clay will increasingly take centre stage in diverse scientific research on, for example, bioreceptive architecture (Dover, 2015) or plastic-use reduction (see Murphy et al., 2016). Clay's presence in, mobility around, and bridging of, diverse scientific disciplines and spaces requires unpacking, particularly with respect to the diverse epistemological sense-making work concerned with what clay *is* and how it might be used. While we have attempted to open up this discussion and line of enquiry here, more work is required to fully theorise and understand clay as a scientific artefact.

REFERENCES

Anderson, B, Cook, I and Maddern J (2006) Geography and matter/materiality. Workshop series sponsored by RGS (IBG) Social and Cultural Geography Group.

Aguzzi, C, Sandrib, G, Cerezoa, P, Carazoa, E and Viseras, C (2016) Health and medical applications of tubular clay minerals. Developments in Clay Science, 7, 708-725.

Badreshany, K (2016) Lebanon's earliest potting traditions in regional context. Berytus, 59, 5-42.

Barad, K (2003) "Posthumanist Performativity: Toward an Understanding of How Matter Comes to Matter." *Signs: Journal of Women in Culture and Society* 28 (3): 801-831.

Barley, N (1994) Smashing pots: feats of clay from Africa. British Museum Press, London.

Belsey, C (2013) Textual analysis as a research method. In Research Methods for English Studies, p160-178, Griffin, G (Ed). Edinburgh University Press, Edinburgh.

Bennett, J (2010) *Vibrant Matter: A Political Ecology of Things*. Durham, NC: Duke University Press.

Bernal, JD and Fankuchen, I (1941) X-ray and crystallographic studies of plant virus preparations. The Journal of General Physiology, 25 (1), 111-154.

Bergaya, F and Lagaly, G (2006) General introduction: clays, clay minerals and clay science, p1-18. In Handbook of Clay Science. Developments in Clay Science, Vol. 1., Bergaya, F, Theng, BKG and Lagaly, G (Eds). Elsevier Science.

Brack, A. (2006) Clay minerals and the origin of life, p379-391. In Handbook of Clay Science. Developments in Clay Science, Vol. 1., Bergaya, F, Theng, BKG and Lagaly, G (Eds). Elsevier Science.

Braun, V and Clarke, V (2013) Successful qualitative research: a practical guide for beginners. Sage, London.

Braun, V and Clarke, V (2019) Reflecting on reflexive thematic analysis. Qualitative Research in Sport, Exercise and Health, 11 (4), 589-597.

Brigatti, MF, Galan, E and Theng, BKG (2006) Structure and mineralogy of clay minerals, p19-86. In Handbook of Clay Science. Developments in Clay Science, Vol. 1. Bergaya, F, Theng, BKG and Lagaly, G (Eds). Elsevier Science.

Brigstocke, J (2016) Exhausted futures. GeoHumanities, 2 (1), 92-101.

Boivin, N (2008) Material cultures, material minds the impact of things on human thought, society and evolution conclusion, Cambridge University Press, Cambridge.

Boivin N and Owoc MA (2004) Soils, stones and symbols: Cultural perceptions of the mineral world, London, Berg.

Chakravartty, A (2017) Scientific ontology: integrating naturalized metaphysics and voluntarist epistomology. Oxford Scholarship Online, DOI: 10.1093/oso/9780190651459.001.0001

Churchman, JG, Gates, WP, Theng, BKG and Yuan, G (2006) Clay and clay minerals for pollution control, p625-675. In Handbook of Clay Science. Developments in Clay Science, Vol. 1., Bergaya, F, Theng, BKG and Lagaly, G (Eds). Elsevier Science.

Dempster, DN, Jones, DL and Murphy, DV (2012) Clay and biochar amendments decreased inorganic but not dissolved organic nitrogen leaching in soil. Soil Research, 50 (3), 216-221.

Dong, H, Jaisi, DP, Kim, J and Zhang, G (2009) Microbe-clay mineral interactions. American Minerologist, 94 (11-12), 1505-1519.

Dover JW (2015) Green infastructure: incorporating plants and enhancing biodiversity in buildings and urban environments. Routledge, London.

Drazin, A and Kuchler, S (Eds.) (2015) The Social Life of Materials: Studies in Materials and Society, Bloomsbury Publishing, Bloomsbury, UK.

Fayers-Kerr K (2019) Becoming a Community of Substance: The Mun, the mud and the therapeutic art of body painting pp. 109-133. In Body Matters: Exploring the Materiality of the Human Body. Attala, L, Steel, L and Zinn, K. (Eds.). University of Wales Press.

Ferraro E (2019) Coins, beads, and necklaces: On light, brilliance, and scredness in the Northern Andes. Material Religion, 15 (5), 577-598.

García, ÉD and de Ágredos Pascual, MLV (2019) Painting the skin: pigments on bodies and codices in pre-Columbian Mesoamerica. University of Arizona Press, Tucson.

Gatabin, C, Talandier, J, Collin, F, Charlier, R and Dieudonne, AC (2016) Competing effects of volume change and water uptake on the water retention behaviour of a compacted MX-80 bentonite/sand mixture. Applied Clay Science, 121-122, 57-62.

Gerson, E (1983) Scientific work and social worlds. Knowledge, 4 (3), 357-377.

Gosselain, OP (1999) In pots we trust: the processing of clay and symbols in sub-Saharan Africa. Journal of Material Culture, 4 (2), 205-230.

Guggenheim, S and Martin, RT (1995) Definition of clay and clay mineral: joint report of the AIPEA nomenclature and CMS nomenclature committees. Clays and Clay Minerals, 43 (2), 255-256.

Hamilton N (2000) Ungendering Archaeology: concepts of sex and gender in figurine studies in prehistory, p17-30. In Representations of Gender from Prehistory to the Present. Studies in Gender and Material Culture, Donald M and Hurcombe L (Eds). Palgrave Macmillan, London.

Haraway, D (1988) Situated knowledges: the science question in feminism and the privilege of partial perspective. Feminist Studies, 14 (3), 575-599.

Haraway, D (2008) *When Species Meet.* Minneapolis: University of Minnesota Press.

Harding, S (1986) The science question in feminism. Cornell University Press, Ithaca and London.

Harvey, CC and Lagaly, G (2013) Industrial applications. Developments in Clay Science, 5, 451-490.

Hayden, C (2003) When nature goes public: the making and unmaking of bioprospecting in Mexico. Princeton University Press, Princeton.

Henry, JM and Cring, D (2013) Geophagy: an anthropological perspective. In Soils and Human Health, Brevik, EC and Burgess LC (Eds). CRC Press, Taylor and Francis Group.

Henry, J and Kwong, AM (2003) Why is geophagy treated like dirt? Deviant Behavior, 24 (4), 353-371.

Hodder, I (2011) Human-thing entanglement: towards an integrated archaeological perspective. Journal of the Royal Anthropological Institute, 17 (1), 154-177.

Hosseinkhani, A, Montaseri, H, Hosamo, A and Zarshenas, MM (2017) An evidence-based review on medicinal value of clays in traditional Persian medicine. Current Drug Discovery Technologies, 14 (1), 2-7.

Ingold, T (2007) Earth, Sky, Wind and Weather, Journal of Royal Anthropological Institute, 13 (1), 19-38.

Ingold, T (2013) Making: Anthropology, Archeology, Art and Architecture, Routledge, UK.

Jamie, K and Sharples, G (2020) The social and material life of medicinal clay: Exploring antimicrobial resistance, medicines' materiality and medicines optimization, Frontiers in sociology, 5.

Jones, A (2004) Archeological Theory and Scientific Practice, Cambridge University Press, Cambridge, UK.

Kothari, U and Arnall, A (2017) Contestation over an island imaginary landscape: the management and maintenance of touristic nature. Environment and Planning A, 49 (5), 980-998. DOI: 10.1177/0308518x16685884

Kothari, U and Arnall, A (2020) Shifting sands: the rhythms and temporalities of island sandscapes. Geoforum, 108, 305-314.

Landa, ER and Feller C (Eds.) (2010) Soil and Culture, Springer, NY.

Levi-Strauss C (1985) La Potière Jelouse [The Jealous Potter]. Pocket, Paris.

Lichtfouse, E (2010) Society issues, painkiller solutions, dependence and sustainable agriculture, p1-17. In Sociology, Organic Farming, Climate Change and Soil Science, Lichtfouse, E (Ed). Springer Netherlands.

Livingstone, DN (2010) Landscapes of knowledge, p3-22. In Geographies of Science, Meusburger, P, Livingstone, D and Jöns, H. Springer, Netherlands.

Matike DME, Ekosse GI and Ngole VM (2010) Indigenous knowledge applied to the use of clays for cosmetic purposes in Africa: an overview. Indilinga, 9 (2), 138-150.

McLoone, P, Warnock, M and Fyfe, L (2016) Honey: a realistic antimicrobial for disorders of the skin. Journal of Microbiology, Immunology and Infection, 49 (2), 161-167.

McMahon, S, Anderson, RP, Saupe, EE and Briggs, DEG (2016) Experimental evidence that clay inhibits bacterial decomposers: implications for preservation of organic fossils. Geology, 44 (10), 867-870.

Moore, DM and Reynolds, RC Jr (1997) X-ray diffraction and the identification and analysis of clay minerals, 2nd Edition. Oxford University Press, Oxford and New York.

Murphy, JL, Ayers, TL, Knee, J, Oremo, J, Odhiambo, A, Faith, SH, Nyagol, RO, Stauber, CE, Lantagne, DS and Quick, RE (2016) Evaluating four measures of water quality in clay pots and plastic safe storage containers in Kenya. Water Research, 104, 312-319.

Parry, LA, Smithwick, F, Nordén, KK, Saitta, ET, Lozano-Fernandez, J, Tanner, AR, Caron, J-B, Edgecombe, GD, Briggs, DEG and Vinther, J (2018) Soft-bodied fossils are not simply rotten carcasses - toward a holistic understanding of exceptional fossil preservation: exceptional fossil preservation is complex and involves the interplay of numerous biological and geological processes. BioEssays, 40 (1), 1-11.

Robinson, GM (2004) Geographies of agriculture, globalisation, restructuring and sustainability. Pearson Education Limited, New York.

Rose, G and Tolia-Kelly, DP (2012) Visuality/materiality: introducing a manifesto for practice, p1-12. In Visuality/materiality: Images, Objects and Practices, Rose, G. and Tolia-Kelly, DP (Eds). Ashgate Publishing, Surrey.

Salazar, JF, Granjou, C, Kearnes, M, Krzywoszynska, A and Tironi, M (Eds) (2020) Thinking with soils, material politics and social theory. Bloomsbury Academic, London.

Salisbury, RB (2012) Engaging with soil, past and present. Journal of Material Culture, 17 (1), 23-41.

Schiffer, MB (2004) Studying technological change: A behavioural perspective, World Archeology, 36 (4), 579-585.

Schiffer, MB and Skibo, James M (1997) The explanation of artifact variability, American Antiquity, 62 (1), 27-50.

Skibo, James M (2013) Understanding Pottery Functions, Springer, New York.

Skibo, James M (1992) Pottery Function: A use alteration perspective, Plenum Press, New York and London.

Skibo, James M and Schiffer, MB (2008) People and things: A behavioural approach to material culture (Manuals in Archeological Method, Theory and Technique), Springer, New York.

Smith, B (2008) Ontology (Science). Nature Precedings, Online: https://www.nature.com/articles/npre.2008.2027.1#article-info

Stevanović M (1997) The age of clay: the social dynamics of house destruction. Journal of Anthropological Archaeology, 16, 334–395.

Taçon, PS (2004) Ochre, clay, stone and art. Soils, Stones and Symbols: Cultural Perceptions of the Mineral World, 31-42.

Thomford, NE, Senthebane, DM, Rowe, A, Munro, D, Seele, P, Maroyi, A and Dzobo, K. (2018) Natural products for drug discovery in the 21st Century: innovations for novel drug discovery. International Journal of Molecular Sciences, 19 (6), 1578.

Weismantel M and Meskell L (2014) Substances: ‘following the material’ through two prehistoric cases. Journal of Material Culture, 19 (3), 233-251.

Wesley, LR (Ed) (2014) Clays and clay minerals: geological origin, mechanical properties and industrial applications. Nova Science Publishers, New York.

Westerhold, T, Röhl ,U and Laskar, J (2012) Time scale controversy: accurate orbital calibration of the early Paleogene, Geochemistry, Geophysics, Geosystems, 13 (6), 1-19.

Williams, LB (2019) Natural antibacterial clays: historical uses and modern advances. Clay and Clay Minerals, 67 (1), 7-24.

Williams, LB and Haydel, SE (2010) Evaluation of the medicinal use of clay minerals as antibacterial agents. International Geological Review, 52 (7/8), 745-770.

Williams, LB, Holland, M, Eberl, D, Brunet, T and Brunet de Courssou, L (2004) Killer Clays! Natural antibacterial clay minerals. Mineralogical Society Bulletin, 139, 3-8.

World Health Organization (2014) Antimicrobial resistance: global report on surveillance. World Health Organization, Geneva.