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PLASTICITY AND TIME: USING THE STRESS-STRAIN CURVE AS A FRAMEWORK FOR INVESTIGATING THE WICKED PROBLEMS OF MARINE POLLUTION AND CLIMATE CHANGE

John Schofield and Celmara Pocock

Introduction

Plastics have very rapidly become the characteristic material of the current Plastic Age, just as stone and metal artefacts characterised and became the type fossils of earlier periods. Plastics have utility and value as everyday items. As such they have become a part of the archaeological record (e.g. Mytum and Meek 2021) and a new category of cultural heritage[1]. However, plastics also present a significant threat to planetary health, forming a particular, disruptive and potentially resilient category of what has become known as toxic heritage (after e.g. Wollentz et al. 2020), the legacies of which will likely extend long into the future, itself now the subject of heritage attention (e.g. Holtorf and Högberg 2021).

In this chapter, we present a temporal framework within which to assess this particular category of toxic heritage: the stress-strain curve (e.g. Beer et al. 2020). This curve recognises that materials pass through a phase of elasticity (in which remediation can bring things back to their 'original' form) towards plasticity (whereby things retain an aspect of their original form but are forever changed) leading ultimately to fracture (where the thing becomes irretrievably broken). We propose that this curve can apply to plastics in two distinct but related ways. First, it can apply to the changing form of plastics, by which they may start as useful and everyday, perhaps even becoming formally recognised as heritage items, to eventually and typically breaking down into potentially dangerous micro- and nano-plastics, becoming at best *in*significant in heritage terms (after Ireland et al. 2020), and at worst destructive. Second, it can apply to the ecosystems that are impacted by plastics: if the problem of plastic pollution is caught early enough, then those ecosystems may be relatively unaffected (elasticity); but if the problem is left untreated, ecosystems might break down altogether (fracture).

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We position this theoretical argument alongside studies that have used archaeological methods within the wider framing of heritage research to address the challenges of plastics and waste (e.g. Ross and Angel 2020). As outlined later in the chapter, ongoing work in Galápagos (Ecuador) has demonstrated how archaeology (in the form of object itineraries) can play an important role alongside oceanographic studies in determining the origins of plastic waste in remote locations (van Sebille et al. 2019; Schofield et al. 2020). Archaeology has also been used to help understand (and potentially, ultimately change) people's behaviours, for example through highlighting the distributions of COVID waste on local and international scales (e.g. Magnani et al. 2022 and Schofield et al. 2021 respectively).

The 'Wicked Problem' of Plastic Pollution

It is hard to imagine a world without plastics, and yet such a world existed until only around seventy years ago. It is true that plastics have earlier origins, but their widespread use only began after the conclusion of the Second World War. From that point on, as Geyer et al. (2017) state, 'the ensuing rapid growth in plastics production is extraordinary, surpassing most other man-made [sic] materials' (see also MacLeod et al. 2021). Currently, according to Geyer et al., some 12% of plastic waste globally is incinerated (itself a major environmental and health problem, e.g. Ágnes and Rajmund 2016) and 9% recycled, with the majority being either disposed into landfills (e.g. Rathje 1992) or being carelessly discarded or lost (including from landfill) to enter the environment. Where plastics end up in the environment they present a particular problem, both for that environment and for its inhabitants (human and non-human).

For example, plastics pollute chemically, 'when added chemicals (monomers and plasticizers) escape plastics and interact with bodies and ecosystems' (after Liboiron 2016, 92). Plastic pollution can jeopardise or threaten vital resources that are the basis of livelihoods and cultural knowledge and practices, degrade natural attributes that are the basis of tourism income, and impact aesthetic qualities that underpin social and cultural attachments to places. Plastics thereby compromise the heritage values of diverse environments with implications for the well-being of local peoples.

In terms of dangers, within the marine environment the majority of recorded pollution has involved entanglement and the ingestion of plastics by marine life. For example, of the 340 publications reviewed by Gall and Thompson (2015), 292 reported ingestion or entanglement involving marine debris and organisms, with plastics by far the most common form of debris (at 92%). Further analysis showed that direct harm or death is a significantly more common consequence of entanglement (at 79%) than of ingestion (at 4%).

Like the plastics themselves, the problem is ubiquitous: plastic debris has been found in every ocean basin as well as in freshwater and terrestrial habitats across the globe. It has now also been found in both animal and human bodies, including in people's lungs (Jenner et al. 2022).

Plastic pollution, alongside the interrelated problem of climate change (see Ford et al. 2022; Lavers et al. 2022,) and health (Romanello et al. 2022), has been referred to as a wicked problem (after Rittel and Webber 1973; Head 2022; see also Schofield in prep.), being a particular type of problem which is, 'complex, intractable, open-ended, unpredictable' (Alford and Head 2017, 397). This particular cluster of wicked problems (plastic pollution, climate change and health) has also been defined as 'super wicked' (after Lazarus 2009; Levin et al. 2012), because there are additional factors at play, including that:

1 time is running out;
2 there is no central authority, or only weak authority, to manage the problem; and that
3 the same actors seeking to solve the problem continue to directly contribute to it.

As Peters (2017) states, the time element is critical where irreversible harm will be done if significant policy interventions are not made, and quickly. Peters (2017, 389) also points out that public sector decision-making is not good at dealing with long-term challenges, especially in democratic regimes where changes in government often also mean changes in policy.

It is widely agreed that wicked problems require creative solutions, sometimes referred to as messy or 'clumsy' solutions (e.g. Grint 2010, 24). This chapter suggests how such creativity, in the form of an archaeological-heritage perspective, might help address the particular wicked problem of marine pollution alongside the related problem of climate change.

The Archaeology of Plastics

Plastics are now a category of cultural heritage: a highly visual and impactful component of an ever-changing and evolving landscape of entangled nature and culture. Plastics have therefore rapidly become type-fossils of a Plastic Age, the definition of which is not new. Over a decade ago, Thompson et al. (2009) referred to 'our plastic age' in a landmark publication for the Royal Society, while Brandon et al. (2019) note how the, 'increase in plastic deposition in the post–World War II years can be used as a geological proxy for the Great Acceleration of the Anthropocene in the sedimentary record' (see also Mytum and Meek 2021). Edgeworth et al. (2022) gave this argument more nuance, focusing on the precise temporal parameters for viewing this category of material within the wider context of debates around the Anthropocene. Having established that 'PET (polyethylene terephthalate) bottles were first produced in 1973, and so date what might be termed the mid- to late Anthropocene', they describe how,

> the patterns into which plastics have been shaped infinitely multiply the dating possibilities. The plastic credit card and the Bic Cristal ballpoint pen, for instance,

both first produced in 1950, may be regarded as zone technofossils for the Anthropocene, while compact discs (surprisingly widely dispersed as trash) only date from 1982. The technostratigraphic possibilities are almost endless, as technodiversity (if measured as the number of specific kinds of technofossil) is now far greater than biodiversity, measured as the number of species.

Beyond dating archaeological sites, these plastics are also indicative of contemporary behaviours. One difference between this contemporary archaeology (and see also Zalasiewicz et al. 2017 in this context) and the study of earlier periods is that archaeologists are not looking back on a deeper past but engaging with the period in which they live, critiquing the very world they shape through their everyday practices (Graves-Brown 2000, 1). Through a critical lens, archaeology can thus become activist as a relevant, engaging and informative mode of enquiry.

The Stress-Strain Curve

The Stress-Strain Curve (Figure 4.1) is well known in engineering and materials science and has been applied to virtually every material, from plastic and glass to concrete (see Beer et al. 2020). As stated earlier, the stress-strain curve is notable for its recognition of the concept of plasticity: that materials pass through a phase of elasticity (in which remediation can bring things back to their 'original' form) towards plasticity (whereby things retain an aspect of their original form, but are forever changed) leading ultimately to fracture (where things become irretrievably broken). Much has been written about stress and strain within plastics and polymers

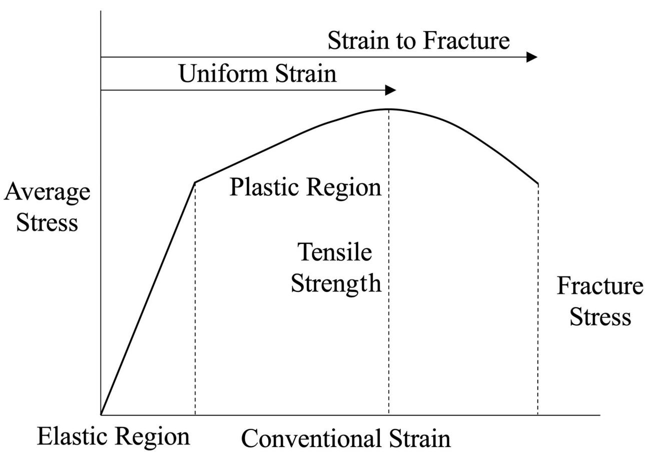

FIGURE 4.1 The Stress-Strain Curve. (Available open source via Wikimedia Commons, https://upload.wikimedia.org/wikipedia/commons/9/98/Stress_Strain.JPG).

(e.g. Williams and Ford 1964; Haward 1987), recognising, for example, that nearly all have a degree of elasticity, particularly during their (often very short) use-life. Unless plastics are conserved in some way, elasticity is gradually reduced as plasticity takes over. In this phase, the plastics will become less flexible, more embrittled. And ultimately the plastic items fracture, creating micro- and nanoplastics that can have a detrimental impact on human and animal health. In the case of object itineraries, discussed below, this curve provides a temporal framework, much as the ageing process does for human and non-human beings.

We suggest that this curve provides a useful model (and terminology) for understanding how plastic becomes toxic heritage, and simultaneously threatens existing heritage values. Here we explore this particular application through two World Heritage Listed archipelagos whose Outstanding Universal Values are impacted by the related wicked problems of plastics pollution and climate change: Galápagos (Ecuador) and the Great Barrier Reef (Australia). (See Table 4.1 for a summary of the key issues).

Within Galápagos, the problem of plastic pollution and its impact on iconic and endemic species was recognised early by those responsible for managing the island's resources. Recalling Grint's (2010) definition of clumsy solutions to wicked problems, specialist advice was sought from outside the remote archipelago, involving scientists from a diverse range of specialisms with the intention that these specialists work alongside locally based scientists and local communities. This degree of trans-disciplinary collaboration was considered essential if solutions were to be ethical, sustainable and have local support. One part of this collaborative effort involved a Science to Solutions workshop and research programme coordinated initially by the Galapagos Conservation Trust (based in London), itself involving scientists from around the world, including the United Kingdom, Europe, Australia and South America.[2] This collaborative network included archaeology, with its focus on material culture bringing a temporal perspective to the problem (Schofield et al. 2020).

This collaborative and transdisciplinary initiative to address the fast-emerging problem of plastic pollution in Galápagos, hoped to catch the problem early enough to ensure the process of change did not extend beyond the elasticity phase in which remediation can bring things back close to an 'original' form. By appropriate action,

TABLE 4.1 The key issues related to the two case studies of Galápagos and the Great Barrier Reef

Wicked Problem	Example	Current emphasis in solution	Stress-Strain Stage	Aim	URL for OUV summary
Plastic pollution	Galápagos	Behaviours	Elasticity → Plasticity	Reversal	https://whc.unesco.org/en/list/1/
Climate change	Great Barrier Reef	Technical	Plasticity → Fracture	Mitigation	https://whc.unesco.org/en/list/154/

it is argued, the problem can be stopped in its tracks, or at least slowed, provided the efforts are then maintained to ensure it does not, once again, get out of hand. This is where the local community becomes so important. Without local support, holding the line and even continuing to reduce the scale of the problem would likely prove impossible.

Part of the clumsy solution to plastic pollution in Galápagos involved using object itineraries (versions of which are also referred to as narratives or biographies), which have long formed a part of material cultural research (e.g. Joyce and Gillespie 2015; after Kopytoff 1986). In the Science to Solutions workshop, the team used object itineraries to investigate a plastic assemblage from a remote beach to help understand the source of the plastic waste accumulating there (Figure 4.2). This was achieved through building stories around each plastic item, one element of which was to use its condition (alongside information from labelling and biofouling) as an indicator of both how long it had first been at sea, and then how long it had been exposed on the beach – identifying its natural and its cultural transformations, in Schiffer's (1976) terms. Through this work, and by combining the evidence for longevity with evidence of the objects' origins including through oceanographic modelling (specifically, van Sebille et al. 2019), Galápagos plastics have predominantly been sourced to the Pacific coast of South America (specifically northern

FIGURE 4.2 Members of the Science to Solutions workshop team collecting a representative sample of plastic objects from a remote beach in Galápagos, in 2018. The objects collected were then subject to 'object itinerary' investigations to help better understand where the items were coming from. (Image: John Schofield).

Peru and southern Ecuador) and to the International fishing fleet, which operates legally immediately beyond the exclusion zone around Galápagos.

In general terms, and relating to the stress-strain curve, plastic objects remain low on the curve to begin with, in the elasticity phase. In this phase, they may sometimes be recognised as valued heritage objects[3]. Perhaps during their use phase, but more usually after discard, the objects enter the plasticity phase. In heritage terms, we can recognise this as a time of vulnerability for plastics where they might hold heritage significance and be conserved, or more likely discarded and at risk of becoming toxic heritage, both as objects lacking integrity and as plastics that fracture, as the objects become brittle and break down into smaller parts. This latter part of the process often coincides with environmental degradation. In this way the object itineraries and the landscape history are enmeshed; the trajectory of one (the environment) being closely entwined with that of the other (plastics).

The impacts of climate change are widespread and catastrophic at the Great Barrier Reef, where a confluence of factors wreaks untold damage on individual reefs and undermines the integrity of the system. The increased magnitude and frequency of extreme weather events cause both immediate physical damage (e.g. uprooted corals), and conditions of vulnerability (e.g. higher nutrient and pollution runoff into reef waters). These changed conditions lead to imbalances, notably in increasing numbers of the naturally occurring Crown-of-Thorns Starfish (COTS). COTS have a voracious appetite for coral polyps, and in large numbers, they ravage swathes of reefs. While reefs can recover between outbreaks of COTS, this takes a couple of decades. But as cyclones repeatedly batter the Great Barrier Reef and the time between COTS outbreaks is reduced, there is insufficient time for such recovery (Westcott et al. 2020). These immediate effects of climate change are amplified by the most compelling of all problems facing the Reef: coral bleaching (or loss of symbionts), which is a response to rising sea temperature and increased UV radiation (Figure 4.3). Cheung et al (2021) describe coral bleaching as 'one of the most striking manifestations of marine heatwaves' that can 'cause mass coral mortality over thousands of hectares within a few months'. These events are also becoming more intense and frequent, with three mass events in just five years (Cheung et al. 2021). And like the COTS outbreaks, the cumulative nature of these impacts could be a tipping point, with Cheung et al. suggesting that 'some reefs will become untenable under repeated stress' (Cheung et al. 2021).

In other words, parts of the Reef remain in the elasticity phase but are likely to degrade due to climate change. Other parts have already reached the plasticity phase at which point change is typically irreparable. It is also possible, if not likely, that areas of the Reef have already fractured, in those places where ecosystems have broken down altogether. Where plasticity and fracture have already been reached, it is hard to see a way back. As Ainsworth et al. (2016, 338) have stated, this bleaching of the coral reefs relates directly to climate change, a wicked problem for which solutions are near impossible: 'We find that near-future increases in local

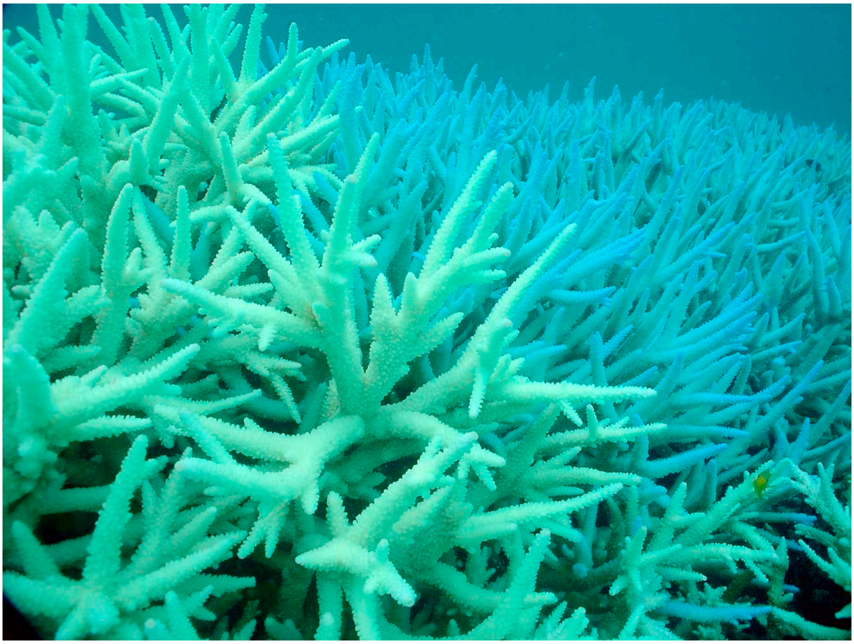

FIGURE 4.3 Bleached corals at Keppel Island, Great Barrier Reef. (Photograph by P. Marshall. Copyright Commonwealth of Australia - GBRMPA).

temperature of as little as 0.5°C result in [the Reef's] protective mechanism being lost, which may increase the rate of degradation'.

Indeed, in the face of what appear to be irreversible impacts, and taking the opposite approach to that being developed in Galápagos, conservation of the Great Barrier Reef has shifted away from efforts to change human behaviours to one focused on finding technical solutions to artificially build and sustain the Reef. These experimental methods include engineering more heat-tolerant species, adding chemical sunshade to the water, and transplanting corals to bleach-affected reefs (Great Barrier Reef Foundation 2017, Suggett et al. 2019). However creative and life-saving these efforts appear, they do not address the stress-strain context produced by exponentially rising sea temperatures and increasingly frequent extreme weather events which have destructive consequences for the Great Barrier Reef (Pocock 2021).

Conclusion

As this chapter has shown, the more nebulous and intractable issue of climate change has pushed the Great Barrier Reef to the point of fracture, while interventions to address the more immediately visible problem of plastic pollution in

Galápagos are helping to secure a position within the elasticity part of the stress-strain curve, whereby things can still revert to an 'original state'. These differences can be viewed within the context of recent arguments that suggest attention to plastic pollution is a distraction from the more pressing and significant issue of climate change (e.g. Stafford and Jones 2019, Jones and Stafford 2021), claims which are rebutted both by arguments that suggest one global issue should not have priority over another in the current planetary crisis (Avery-Gomm et al. 2019), and by evidence that plastic contributes directly to climate change including through the production of Greenhouse Gases (GHGs) through every stage of their lifecycle; from extraction, through production and consumption, to End of Life (Walker et al. 2021, Ford et al. 2022, Bauer et al. 2022). Others point out that far from diverting resources from climate change, plastic pollution has received far less research attention and funding (Lavers et al. 2022).

One of the advantages of plastic pollution over climate change in attracting public support is its immediacy; people can see the pollution and literally pick it up. Yet while one of these wicked problems may be more tangible than the other, both are cumulative and require urgent action beyond such expedient action. While these time pressures are particularly difficult for people to comprehend or to act upon, the temporal framework presented here offers a different way of thinking. Rather than focusing on immediate risk, threat and priorities, we suggest using the stress-strain curve to determine where we are on the trajectory of change, and what can still be realistically achieved. Additionally, object itineraries make this sense of time more explicit and enable communities to understand how time is implicated in the emergence of toxic heritage. By making time explicit through the stress-strain curve, this framework can be used to help understand interconnected trajectories that on the one hand risk transforming plastics into toxic heritage, and on the other recognise how the creation of toxic heritage becomes its own source of stress-strain in ecological systems that underpin World Heritage values. These heritage approaches can also be invoked to help build temporal appreciation of other wicked problems including less visible, environmental challenges, such as climate change.

Notes

1 The Getty Conservation Institute, for example, has a long-term project on the conservation of plastics - https://www.getty.edu/conservation/our_projects/science/plastics/
2 The workshop from 2018 is summarised in Schofield et al. 2020; Pacific Plastics: Science to Solutions is now a GCRF-funded project centred on Exeter University - https://www.pacificplasticssciencetosolutions.com/partners/
3 A child's shoe (one of the Galápagos objects investigated by the team) may have been worn by several children at different times, passing down from one sibling to the next. This is an example of an object that may have been valued as a heritage item (described in Schofield et al. 2020).

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