An anthropogenic marker horizon in the future rock record

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ABSTRACT

Recognition of increasing plastic debris pollution over the last several decades has led to investigations of the imminent dangers posed to marine organisms and their ecosystems, but very little is known about the preservation potential of plastics in the rock record. As anthropogenically derived materials, plastics are astonishingly abundant in oceans, seas, and lakes, where they accumulate at or near the water surface, on lake and ocean bottoms, and along shorelines. The burial potential of plastic debris is chiefly dependent on the material's density and abundance, in addition to the depositional environment. Here, we report the appearance of a new "stone" formed through intermingling of melted plastic, beach sediment, basaltic lava fragments, and organic debris from Kamilo Beach on the island of Hawaii. The material, herein referred to as "plastiglomerate," is divided into in situ and clastic types that were distributed over all areas of the beach. Agglutination of natural sediments to melted plastic during campfire burning has increased the overall density of plastiglomerate, which inhibits transport by wind or water, thereby increasing the potential for burial and subsequent preservation. Our results indicate that this anthropogenically influenced material has great potential to form a marker horizon of human pollution, signaling the occurrence of the informal Anthropocene epoch.

INTRODUCTION

Plastics, or synthetic organic polymers, are lightweight, durable products that are used for a number of consumer and non-consumer goods (Barnes et al., 2009). As anthropogenically derived materials, plastics only began to appear in the 1950s, with production and disposal rates increasing steadily over the past 60 years (Ryan and Moloney, 1993; Moore, 2008). Combined with abysmal rates of recovery, a massive amount of plastic debris has accumulated in Earth's waterways and along shorelines (Derraik, 2002; Thompson et al., 2004; Corcoran et al., 2009; Law et al., 2010). These plastics have been proven dangerous to marine organisms and seabirds through ingestion, entanglement, and disruption of feeding patterns (Laist, 1997; Eriksson and Burton, 2003; Boren et al., 2006; Gregory, 2009; Aloy et al., 2011). In addition, adsorption of persistent organic pollutants (POPs) onto plastics (Mato et al., 2001; Endo et al., 2005; Rios et al., 2007, 2010) enhances the potential for bioaccumulation from ingested microplastics into fish. The unknown effect on apex predators, such as humans, is a major concern. These POPs, such as polychlorinated biphenyls (PCBs), can cause serious health effects, as they have been shown to be endocrine-disrupting chemicals and carcinogens (Bergman et al., 2013).

The degradation of plastic material is a slow process that can occur mechanically, chemically (thermo- or photo-oxidative), and to a lesser degree, biologically (Kulshreshtha, 1992; Shah et al., 2008; Cooper and Corcoran, 2010). The persistence of plastic in the environment has been estimated to be in the range of hundreds to thousands of years, although longevity can increase in cool climates and where material is buried on the ocean bottom or under sediment (Gregory and Andrady, 2003). A recent study examining the accumulation of marine ocean debris at depths of 25–3971 m over a 22-year period shows that 33% of all debris in Monterey Bay, California, USA, is composed of plastic litter (Schlining et al., 2013). Similar results from other localities reveal that much of plastic debris is below the water surface (Goldberg, 1997; Galgani et al., 2000; Keller et al., 2010). This debris may be composed of high-density plastics or low-density plastics with fouled surfaces (Ye and Andrady, 1991; Goldberg, 1997; Gregory, 2009; Lobelle and Cunliffe, 2011). Given the low water temperatures and decreased exposure to UV light at greater depths within and below the photic zone, sunken plastic debris has good potential to persist and eventually form part of the rock record. On beaches, plastic debris, such as resin pellets, fragments, and expanded polystyrene up to 11 mm in size, may be preserved within the upper 5 cm of beach sediment (Kusui and Noda, 2003). Claessens et al. (2011) identified microplastics in beach sediment cores at depths down to 32 cm. In addition, Fisner et al. (2013), in their study of polycyclic aromatic hydrocarbons in pellets, were able to locate plastic debris at sediment depths as great as 1 m. However, we found no visible loose plastic fragments at depths >10 cm in sand on Kamilo Beach, Hawaii. Given the beach's constant exposure to the northeasterly trade winds, much of the small (<10 cm), lightweight plastic debris is blown to the backshore environment, where it becomes trapped in vegetation. On a beach as dynamic as Kamilo, preservation of plastics in the sediment column could occur where trapped sediment is covered with sand or where a polymer is combined with a much denser material. We observed the results of this density increase on Kamilo Beach, where great quantities of melted plastic have mixed with the substrate to create new fragments of much greater density, herein referred to as "plastiglomerate."

CHARACTERISTICS OF KAMILO BEACH

The location of the Hawaiian Islands within the North Pacific subtropical gyre makes them vulnerable to acting as sinks for plastic debris (Moore, 2008). The anticyclonic movement of surface ocean currents within the gyre results in preferential

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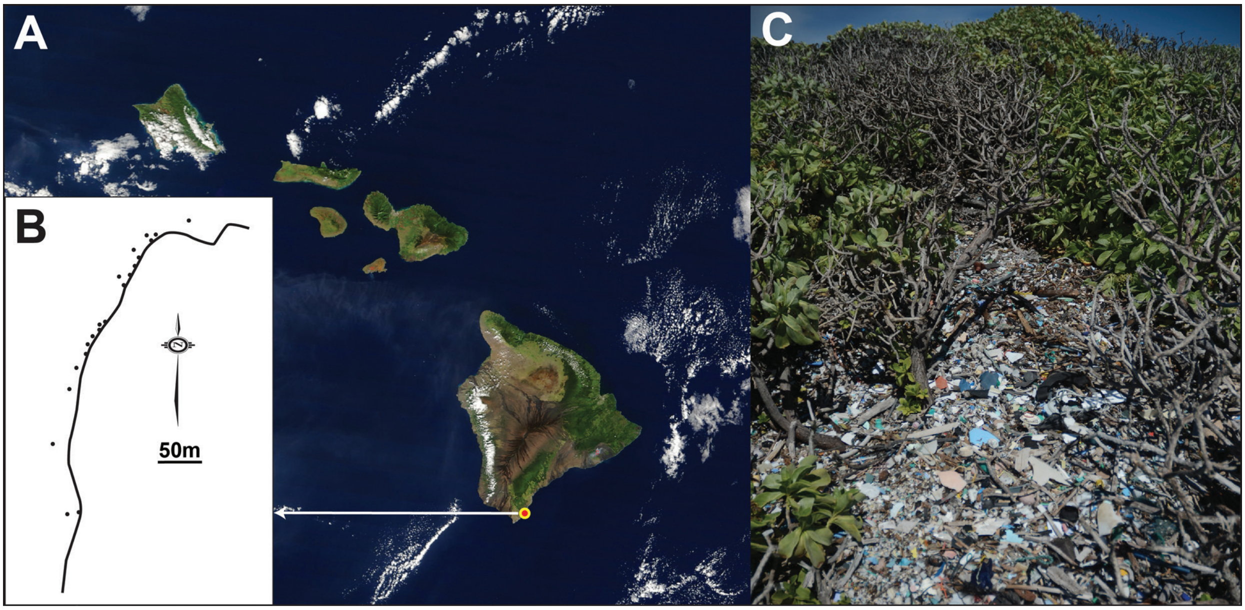

Figure 1. Location and characteristics of Kamilo Beach. (A) Location of Kamilo Beach along the southeast shore of the island of Hawaii (satellite image of 13 Dec. 2002, available at http://visibleearth.nasa.gov). (B) Sampling locations along the Kamilo Beach shoreline (Pacific Ocean east of the dark line). (C) Plastic "confetti" trapped within vegetation.

deposition of marine debris along the eastern and southeastern windward shorelines of the major Hawaiian Islands (Corcoran et al., 2009; McDermid and McMullen, 2004). Kamilo Beach, located on the southeastern tip of the island of Hawaii, is notable for its accumulation of vast amounts of marine debris (Moore, 2008) (Figs. 1A and 1B). Typical plastic debris include derelict fishing gear, including nets, oyster spacer tubes and buoys; food and drinking containers; resin pellets; and abundant multi-colored fragments or "plastic confetti" (Fig. 1C). The main stretch of Kamilo Beach is ~700 m long, and its northern termination is marked by a rocky headland jutting 300 m oceanward at low tide. The beach is accessible by four-wheel drive vehicle only, and it is an ~12 km drive from the nearest paved road. The remoteness of the beach plays an important role in the formation of a potential plastiglomerate marker horizon, as most visitors camp for extended periods of time and build fires for cooking and warmth. In addition, regular, organized beach clean-ups are difficult.

FORMATION OF PLASTIGLOMERATE ON KAMILO BEACH

We use the term plastiglomerate to describe an indurated, multi-composite material made hard by agglutination of rock and molten plastic. This material is subdivided into an in situ type, in

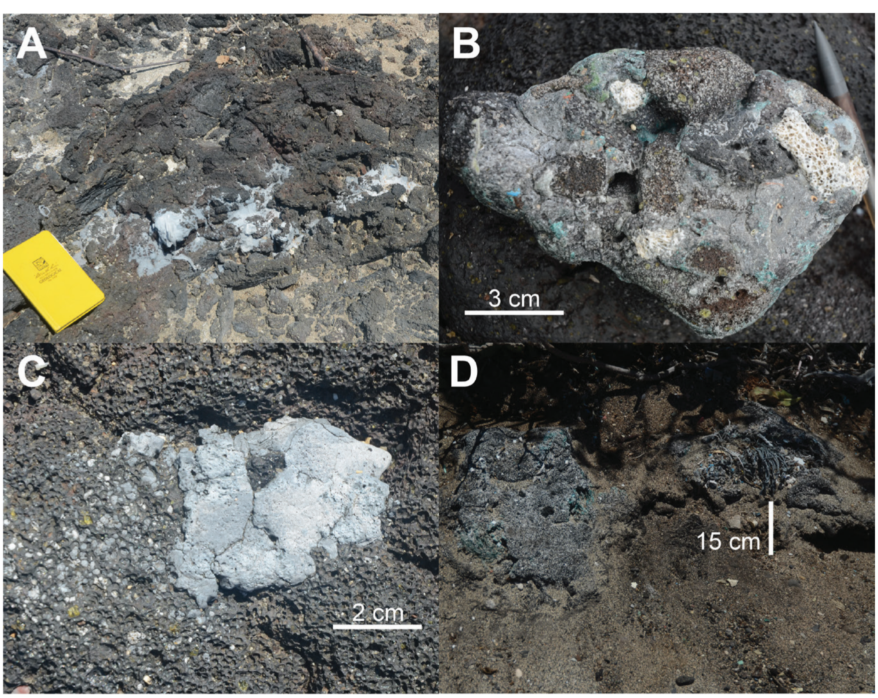

Figure 2. Characteristics of the two types of plastiglomerate. (A) In situ plastiglomerate wherein molten plastic is adhered to the surface of a basalt flow. Field book is 18 cm long. (B) Clastic plastiglomerate containing molten plastic and basalt and coral fragments. (C) Plastic amygdales in a basalt flow. (D) Large in situ plastiglomerate fragment. Adhered molten plastic was found 15 cm below the surface. Note the protected vegetated location.

which plastic is adhered to rock outcrops, and a clastic type, in which combinations of basalt, coral, shells, and local woody debris are cemented with grains of sand in a plastic matrix (Figs. 2A and 2B). Of the 21 sample locations containing plastiglomerate on Kamilo Beach, in situ plastiglomerate was identified at nine. Partially melted polymers adhered to basalt outcrops included fishing nets, piping, bottle caps, and rubber tires. Locally, molten plastic had infilled vesicles in volcanic rock, thereby forming plastic amygdales (Fig. 2C). The largest surface exposure of in situ plastiglomerate was 176 × 82 cm, which was evident only following removal of 15 cm of beach sediment (Fig. 2D). Beach sand and woody debris were locally adhered to the plastic surfaces. Based on its location in more sheltered regions of the beach or within depressions of volcanic rock outcrops, in situ plastiglomerate is interpreted to represent campfire debris.

Clastic plastiglomerate fragments, >2 cm in size, were collected from 21 locations along Kamilo Beach. In addition, we measured the abundance and sizes of angular, clastic plastiglomerate fragments in a quadrat measuring 5 m × 5 m. Partially buried, fractured, in situ plastiglomerate at the center of the quadrat is interpreted as the source of the angular fragments. One hundred and sixty-seven fragments were identified, ranging in size from 2.0 to 22.5 cm, with 55% represented by fragments <4.5 cm. In contrast to the angular nature of the fragments within the quadrat, clastic plastiglomerate fragments found closer to the water and along the strandline were rounded (Fig. 2B) as a result of abrasion in the foreshore environment. A total of 205 fragments sampled from Kamilo Beach displayed different combinations of coral pebbles, plastic, basalt pebbles, woody debris (including charcoal, nuts, and seeds), and sand (including shell fragments) (Fig. 3A). Angular fragments <4 cm in size mainly comprised the sand-plastic group, whereas larger angular fragments were predominantly composed of sand, plastic, basalt pebbles, and woody debris. This discrepancy may be a result of the preferential weathering of organic woody debris and charcoal from the larger fragments, leaving smaller fragments devoid of organic material.

Although plastic debris in some plastiglomerate fragments was melted beyond recognition, we were able to identify distinct types of plastic in most samples. Plastic types included netting/ropes, pellets, partial containers/packaging, lids, tubes/pipes, and "confetti" (Figs. 4A–4D). The latter plastic type was most abundant, as it represents the embrittled remains of intact products, such as containers (Fig. 3B). Partial containers and lids were preserved and were identified in 22% of all fragments. Approximately 20% of the samples contained evidence of fishing-related debris, as indicated by netting, ropes, nylon fishing line, as well as remnants of oyster spacer tubes. We observed that some of the plastiglomerate had been buried by sand and organic debris, as well as having been trapped within vegetation, which demonstrates the potential for preservation in the future rock record.

We measured the bulk density of 20 clastic plastiglomerate fragments sampled from Kamilo Beach. Bulk density of the clastic fragments ranged from 1.7 to 2.8 g/cm^3, with the highest values determined from fragments rich in basalt pebbles. The measured bulk densities show that plastiglomerate has greater potential to become buried and preserved in the rock record than plastic-only particles, which typically have densities in the range of 0.8–1.8 g/cm^3 (Kholodovych and Welsh, 2007).

SOURCE OF MOLTEN PLASTIC

Although the island of Hawaii is volcanically active, the recorded locations of flowing lava over the past century are not coincident with the location of Kamilo Beach. Therefore, the plastiglomerate we sampled from Kamilo Beach cannot be the result of molten lava and polymer interaction. These plastiglomerate fragments were formed anthropogenically. Burning plastic debris in an open environment results in the release of chemical substances, such as carbon monoxide, polycyclic aromatic hydrocarbons, and dioxins (EPA, 2013). These pollutants can cause neurological symptoms, cancer, and hormonal disruptions in humans. In this regard, Kamilo Beach provides an example of an anthropogenic action (burning) reacting to an anthropogenic problem (plastics pollution), resulting in a distinct marker horizon of the informal Anthropocene epoch. Although campfire burning is responsible for the plastiglomerate on Kamilo Beach, it is conceivable that the global extent of plastic debris could lead to

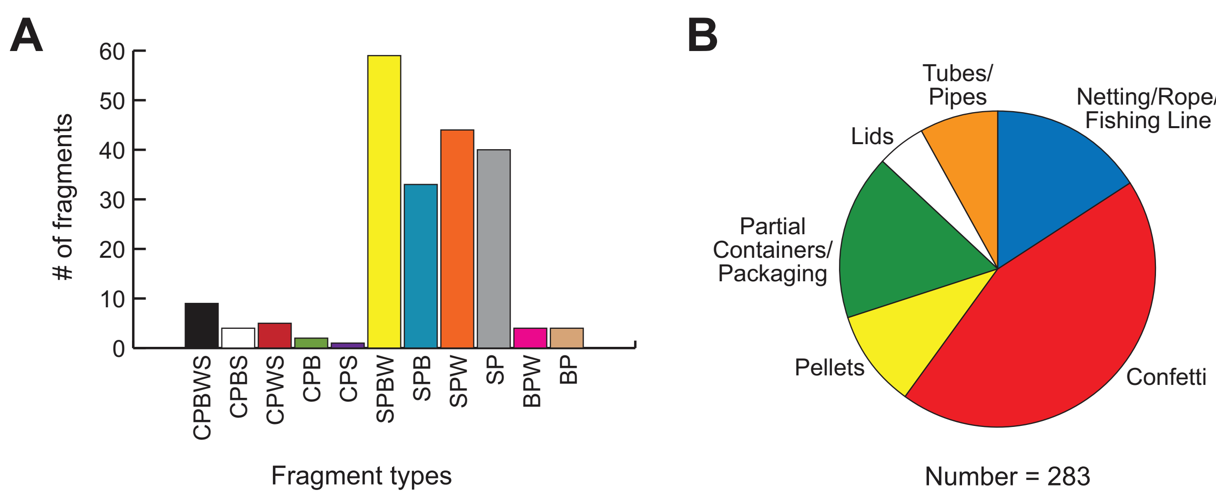

Figure 3. Diagrams illustrating the types of plastiglomerate and relative percentages of adhered plastic fragments. (A) Material composing the sampled plastiglomerate: B—basalt clasts; C—coral fragments; P—plastic; S—sand and sand-size shelly fragments; W—woody debris. (B) Pie diagram showing the relative abundance of different plastic products in plastiglomerate.

Figure 4. Photographs of clastic plastiglomerate on Kamilo Beach. (A) Subrounded fragment containing basalt clasts, molten plastic, yellow rope, and green and red netting. (B) Portions of black and green plastic containers adhered to basalt fragments and connected by netting. (C) Fragment containing plastic pellets and "confetti" with woody debris. (D) Adhered mixture of sand, black tubing, a bottle lid, "confetti," netting, and part of a plastic bag.

similar deposits where lava flows, forest fires, and extreme temperatures occur.

INFORMAL ANTHROPOCENE EPOCH

According to the geologic timescale, we are currently living in the Holocene epoch. However, Crutzen and Stoermer (2000) proposed the term "Anthropocene" to represent the period of time between the latter half of the 18th century and the present day. Although other workers have considered the onset of this informal epoch to have occurred at slightly different times (Ruddiman, 2003; Doughty et al., 2010), researchers agree that the Anthropocene is a time span marked by human interaction with Earth's biophysical system (Zalasiewicz et al., 2011; Syvitsky, 2012). Geological evidence used in supporting this assertion comes from Holocene ice cores and soil profiles. For example, methane concentrations measured in ice cores display an increase at ca. 5000 yr B.P., which contrasts with the expected decline in CH_4 at that time, based on the orbital-monsoon cycle theory (Ruddiman and Thomson, 2001). Ruddiman and Thomson propose that this anomalous rise in CH_4 can be linked to early agricultural practices in Eurasia. In addition, an increase in atmospheric CO_2 at ca. 8000 yr B.P., as determined from ice cores, was explained by Ruddiman (2003) as a result of early forest clearance.

Soil profiles from peat bogs in Norway indicate an increase in lead concentrations in Europe over the past 300 years (Dunlap et al., 1999). Lead concentrations prior to ca. 1950 AD are attributed to mining activities, whereas a second Pb compositional signature in soil younger than 1950 AD is consistent with atmospheric lead derived mainly from combustion of leaded gasoline. Certini and Scalenghe (2011) suggested that anthropogenic soils are the "golden spikes" for the Anthropocene because they contain evidence of soil management practices for enhancing fertility. Examples include terracing, and formation of mixed charcoal, manure, plant debris, and animal bones.

Atmospheric compositions and soil management practices are only two indicators of anthropogenic activity, but relatively few examples of solid, human-made materials are preserved in the sediment record (Zalasiewicz et al., 2008). Even rarer are items that are correlatable on a global scale. Given the ubiquity of non-degradable plastic debris on our planet, the possibility of their global preservation is strong. Our study presents the first rock type composed partially of plastic material that has strong potential to act as a global marker horizon in the Anthropocene.

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