



Plastics and beaches: A degrading relationship

Patricia L. Corcoran^{a,*}, Mark C. Biesinger^b, Meriem Grifi^a

^aDepartment of Earth Sciences, University of Western Ontario, London, ON, Canada N6A 5B7

^bSurface Science Western, Room G-1, Western Science Centre, University of Western Ontario, London, ON, Canada N6A 5B7

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ABSTRACT

Plastic debris in Earth's oceans presents a serious environmental issue because breakdown by chemical weathering and mechanical erosion is minimal at sea. Following deposition on beaches, plastic materials are exposed to UV radiation and physical processes controlled by wind, current, wave and tide action. Plastic particles from Kauai's beaches were sampled to determine relationships between composition, surface textures, and plastics degradation. SEM images indicated that beach plastics feature both mechanically eroded and chemically weathered surface textures. Granular oxidation textures were concentrated along mechanically weakened fractures and along the margins of the more rounded plastic particles. Particles with oxidation textures also produced the most intense peaks in the lower wavenumber region of FTIR spectra. The textural results suggest that plastic debris is particularly conducive to both chemical and mechanical breakdown in beach environments, which cannot be said for plastics in other natural settings on Earth.

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1. Introduction

Beaches across the globe are littered with plastic debris, which pose an imminent threat to marine organisms (Gregory, 1978; Thompson et al., 2004; Oigman-Pszczol and Creed, 2007; Storrer et al., 2007). Plastic fragments on beaches are derived either (1) from inland sources and are transported to coasts by rivers, wind, man-made drainage systems or human activity, or (2) directly from the oceans where low density floating varieties accumulate and are transported across great distances. Floating plastic fragments in the world's oceans have been reported since the early 1970's (e.g. Carpenter and Smith, 1972; Colton et al., 1974), with the amount of debris showing a documented exponential increase into the early 1990's (Ryan and Moloney, 1993). Broken or discarded fishing gear, pellets, scrubbers, microplastics, films, and flakes are the most common plastic debris on beaches and at sea (Carpenter and Smith, 1972; Colton et al., 1974; Moore et al., 2001; Derraik, 2002; Thompson et al., 2004). The majority of these items are non-biodegradable and can attract encrusting organisms as drift plastics (e.g. Winston, 1982; Gregory, 1983; Minchin, 1996), and easily entangle or be ingested by marine organisms including birds, fish, turtles, and mammals (e.g. Rothstein, 1973; Blight and Burger, 1997; Baird and Hooker, 2000; Mallory et al., 2006). Types and amounts of plastic debris on beaches are controlled mainly by topography, current and storm activity, proximity to litter sources and extent of beach use (Storrer et al., 2007).

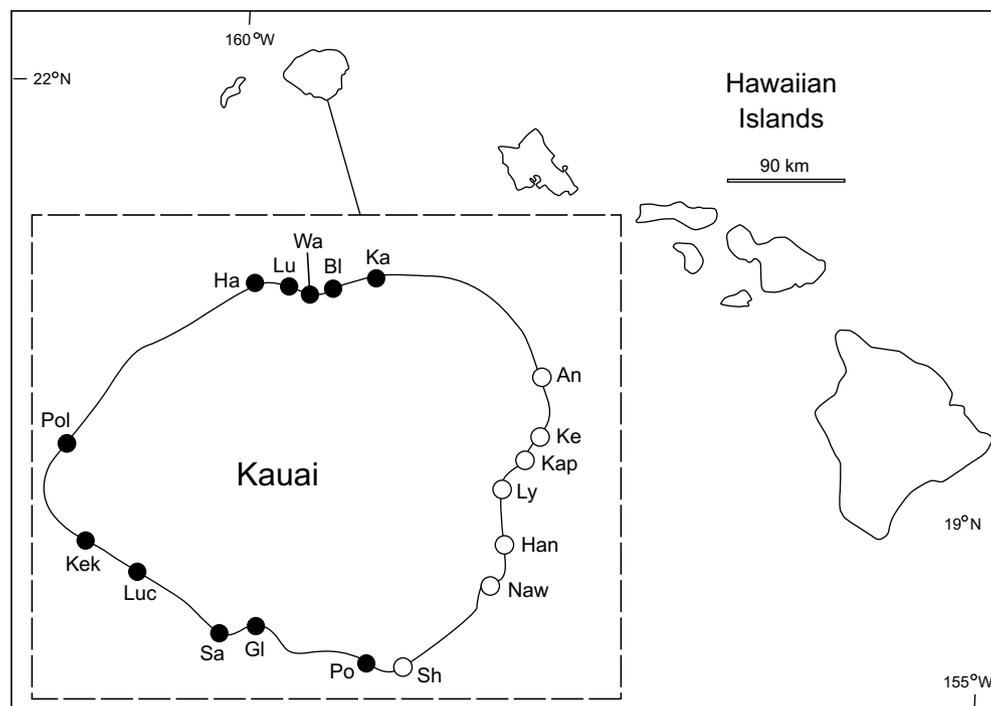
Deposition and retention of plastics on beaches however, are largely controlled by the composition and degradation rates of the plastic particles.

We collected sediment samples from 18 beaches on the island of Kauai to determine the spatial distribution of plastic particles, and to examine the relationships between particle composition and surface textures. No previous publications concerning plastic debris have included textural analyses, which provide clues regarding the extent of mechanical and chemical breakdown of plastics in beach settings.

2. Study area and methods

The Hawaiian Islands are located within the North Pacific Central Gyre, an ocean region containing an extensive accumulation of floating debris (Moore et al., 2001; Pichel et al., 2007). Eighteen beaches on the island of Kauai were sampled for plastic debris, although only seven located along the east coast contained plastic materials visible to the naked eye (Fig. 1). Approximately 150–190 g of sediment was sampled from strandlines at each beach using a small stainless steel trowel. An additional seven samples were collected from Lydgate beach at depths of 1 cm and 10 cm along a 6 m long traverse perpendicular to the shoreline. Each sample was placed in a sodium polytungstate solution with a density of 1.4 g/mL. Particles with specific gravities of <1.4 floated and were then filtered and placed in beakers. The particles were then immersed in a sodium polytungstate solution with a density of 1.2 g/mL and in ethanol:water mixtures of various densities, including 1 g/mL, 0.9549 g/mL, 0.9408 g/mL, and 0.911 g/mL,

* Corresponding author. Tel.: +1 519 661 2111x86836; fax: +1 519 661 3198.
E-mail address: pcorcor@uwo.ca (P.L. Corcoran).



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Fig. 1. Sediment sample locations on Kauai, Hawaiian Islands. Open circles represent locations where >1 mm size plastic particles were visible macro- and microscopically. Closed circles indicate beaches containing no mm-size plastic debris following microscopic examination. Beaches: An, Anahola; Ke, Kealia; Kap, Kapaa; Ly, Lydgate; Han, Hanamaulu; Naw, Nawiliwili; Sh, Shipwreck; Po, Poipu; Gl, Glass (Port Allen); Sa, Salt Pond; Luc, Lucy Wright; Kek, Kekaha; Pol, Polihale; Ha, Haena; Lu, Lumahai; Wa, Waioli; Bl, Black Pot; Ka, Kalihiwai Bay.

which helped determine plastic types. Nineteen plastic particles were examined using a Nikon SMZ-1500 stereo microscope. Surface textures were examined and digitally captured using a Hitachi S-4500 field emission scanning electron microscope (FESEM) using a 15 kV electron accelerating voltage and a 30° sample tilt. Plastic samples were given a light conductive coating of gold prior to analysis to prevent sample charging. Fourier transform infrared spectroscopic (FTIR) analyses were carried out using a Bruker IFS55 FTIR equipped with a microscopic stage attachment. Plastics were analyzed either using thin slices mounted in a diamond compression cell (bulk analysis) or using a micro attenuated total reflection (micro-ATR) attachment (surface oxidation analysis).

3. Textural and compositional results

The plastic particles examined ranged in size from 0.8 to 6.5 mm and were predominantly flakes of larger items, but minor spherical industrial pellets were also identified. The flakes were of various shapes and colours with angular to rounded edges (roundness scale according to Powers, 1953). Surface textures were similar to those typical of sand grains and included pits, conchoidal fractures, linear fractures, adhering particles, subparallel ridges, and grooves (Table 1; Fig. 2). The majority of angular to subangular particles contained conchoidal fractures, whereas linear fractures and adhering particles were more common with increasing grain roundness. Particles with linear fractures were generally more oxidized than those with smooth surfaces, pits and conchoidal fractures, as indicated by granular textures in SEM (Fig. 3A and B). Particle edges parallel to linear fractures were also preferentially oxidized (Fig. 3B).

Dense liquid separation revealed that no sediment samples collected from below the surface of Lydgate beach contained plastic

particles. All plastics sampled from strandlines were composed of polyethylene, except for one polypropylene flake (Table 1). FTIR analysis of 17 samples produced spectra typical of polyethylene with peaks around 2919, 2851, 1473, and 719 wavenumbers (Fig. 3C). The polypropylene particle produced five distinct peaks between 2723 and 2950 wavenumbers, and numerous peaks in the lower wavenumber region between 1453 and 809, similar to standard spectra for polypropylene. Surface oxidation was indicated by more intense absorption peaks for oxidized species in their FTIR spectra (Fig. 3C).

4. Discussion

Macro- and microscopic beach plastics on Kauai could be primarily derived from inland sources, but their distribution appears to be spatially constrained to the east coast (Fig. 1). Although beaches along the north and south coasts are heavily populated, they do not contain abundant plastic litter. Concentration of debris along the east coast may be a consequence of the clockwise rotating ocean currents in the North Central Pacific Gyre and those travelling around the island. As floating debris approaches the northeast coast, longshore currents trap and transport the material parallel to shore, depositing it in a zigzag fashion. This process, combined with flood tides, results in deposition of plastic debris along high water marks (strandlines).

Based on our results, mechanical erosion processes were responsible for most of the surface textures on the Kauai beach plastics. Subangular to subrounded particles, conchoidal and linear fractures, and subparallel ridges were created during particle-particle impacts and saltation, whereas grooves developed from sand grains dragging across plastic surfaces. Adhering clay particles, which may have been derived from chemical weathering of beach

Table 1
Textural characteristics of sampled plastics from beaches of Kauai

Particle	Composition	Size (mm)	Roundness	Surface textures	Oxidation (SEM)
LP91A	PP	1.38	Rounded	Adhering particles, conchoidal fractures	High
KPP91A	PE	6.50	Subrounded	ND	ND
KPP94A	PE	2.25	Subangular	Adhering particles, subparallel ridges	Low
KPP1A	PE	3.75	Subrounded	ND	ND
KPP1B	PE	2.00	Rounded	Linear fractures, grooves	High
KPP1C	PE	2.25	Subangular	Conchoidal fractures	Low
KPP1D	PE	2.63	Rounded (pellet)	Adhering particles, linear fractures, pits	Low
KPP1E	PE	2.38	Subangular	Subparallel linear fractures, pits, conchoidal fractures	High
KPP1F	PE	1.88	Angular	ND	ND
HA1A	PE	3.00	Angular	Pits	Low
HA1B	PE	0.80	Angular	ND	ND
LP95A	PE	3.20	Angular	Pits	Low
LP95B	PE	5.00	Angular	Conchoidal fractures	Low
LP95C	PE	3.25	Rounded (pellet)	Pits	Low
LP95D	PE	4.38	Subangular	Linear, irregular and conchoidal fractures	High
LP95E	PE	3.88	Subrounded	Adhering particles, linear fractures, pits	Medium
LP95F	PE	3.00	Angular	Subparallel ridges	Low
LP95G	PE	3.25	Rounded	Pits	Low
LP95H	PE	2.50	Subrounded	ND	ND

Roundness refers to the shape of the particle edges, which depends on the amount of mechanical weathering (abrasion) that has occurred. Oxidation, in this table is based on the amount of granular textures visible in SEM. ND, no data; PP, polypropylene; PE, polyethylene.

sand, accumulated on plastic fragments during saltation along the beach. Pits identified on almost half of the plastic samples (Table 1) indicate that some degree of dissolution (chemical weathering) occurred either while the particles were floating at sea or while resting on the beach. Degradation of plastic particles is more apt to occur on land than in the oceans where exposure to UV radiation and mechanical erosion is minimal (Gregory and Andrady, 2003). Subangular to rounded flakes dominated by linear fractures and adhering particles were preferentially oxidized compared with

more angular varieties containing conchoidal fractures. The latter particles represent plastics with lower beach residence times than the mechanically rounded flakes. The tendency for linear fractures and particle edges to contain oxidation products indicates that fractures created by mechanical erosion were favourable loci for chemical weathering processes. Oxidation from exposure to solar UV radiation increased plastic degradation, and with additional abrasion, resulted in breakages along fractures, eventually leading to plastic embrittlement.

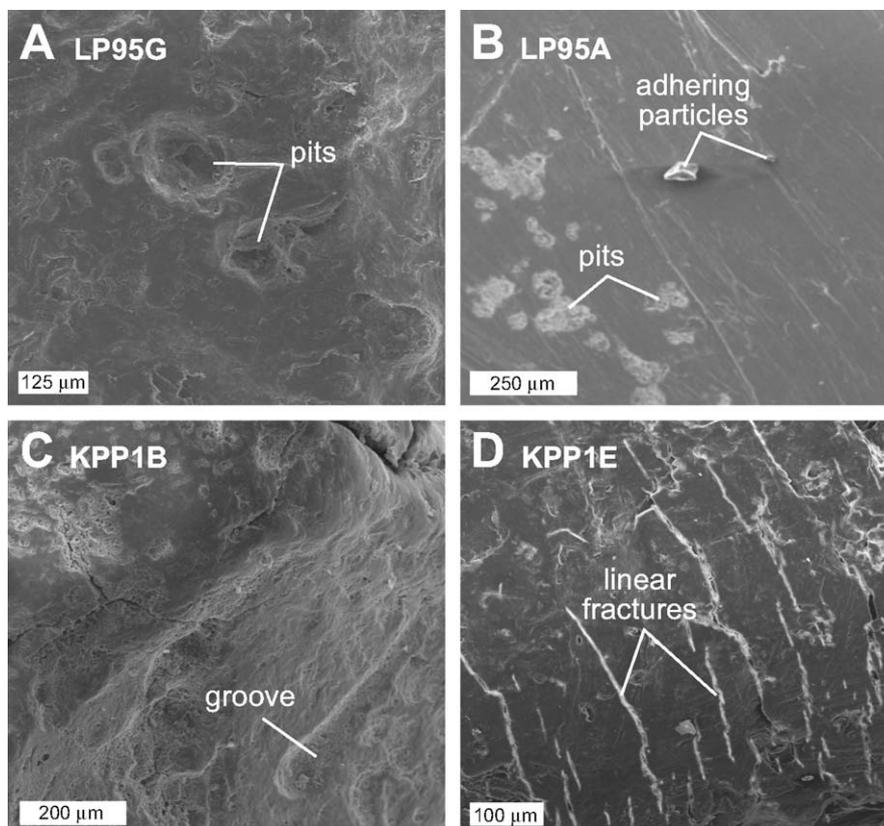


Fig. 2. Examples of surface textures on sampled plastic particles. (A) Pitted surface on rounded sample LP95G. (B) Adhering particles and pits on angular sample LP95A. (C) Groove in rounded, highly oxidized sample KPP1B. (D) Linear fractures in subangular sample KPP1E.

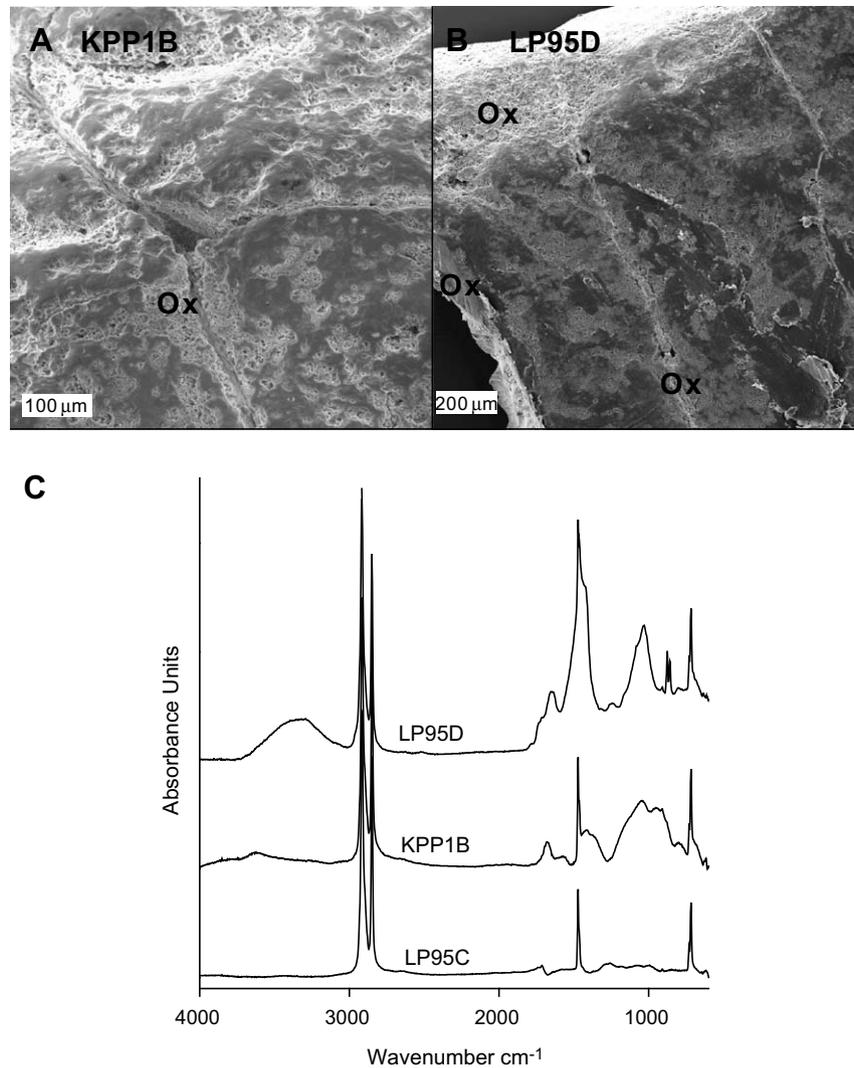


Fig. 3. Evidence of chemical weathering of sampled plastic particles. (A) Granular texture caused by oxidation (Ox) of plastic particle KPP1B. Note how oxidation follows fractures that were formed by earlier mechanical processes. (B) Plastic particle LP95D with oxidized fractures and highly oxidized particle margins. Note the sharp particle margin in the lower left corner of the photograph, which is parallel to the predominant fracture pattern. (C) FTIR spectra from three plastic particles sampled. LP95C is an industrial pellet with low surface oxidation, as indicated by minimal peaks in the lower wavenumber region of the spectrum. Particle KPP1B shows some degree of oxidation, indicated by increased peaks in the lower wavenumber region. Particle LP95D is the most oxidized, as illustrated by the highest peaks in the lower wavenumber spectrum and the broad peak around wavenumber 3300, consistent with the presence of hydroxyl functionality.

Our preliminary results show that beaches represent excellent depositional settings for the diminution of plastic debris, as few other natural environments combine high enough degrees of both chemical and mechanical weathering. In beach environments, chemically and mechanically labile minerals, such as feldspars and clays, are easily broken down and washed out to sea. Unfortunately, plastics do not degrade rapidly through mineralization, and may remain in microscopic form indefinitely. Combining textural evaluations with compositional analyses is significant in unravelling the process of plastics degradation in beach settings, as plastic material is continually being supplied to the world's coastlines (Williams and Tudor, 2001). Additional studies incorporating detailed textural analyses of plastics could provide crucial clues concerning the behaviour of polymers under various natural weathering conditions and environments.

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