Organics: Sources and Depositional Environments

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Synonyms
Detrital organic matter; Nonliving organic matter; Organic carbon; Organic matter

Definition
“Organics” is the short form used for detrital organic matter. It is the nonliving remains of organisms found in sediments, soils, and water. It is comprised of organic molecules often in macromolecular form.

Introduction
The sequestration of organic matter (OM) in depositional environments controls the levels of CO$_2$ in the atmosphere, the global carbon cycle, and hence, climate. The fate of organic matter that is transported from the land to the sea remains one of the fundamental questions in global carbon cycling (Hedges et al. 1997) even after decades of research (Bianchi et al. 2017). There is general agreement that continental shelves represent the largest sink of both terrestrial and marine organic carbon globally, with estimates suggesting that as much as much as a quarter of the total carbon buried in marine sediments is of terrestrial origin (Berner 1982; Hedges and Keil 1995; Raymo 1997). Two important controls on the preservation of organic matter are the composition of the organic matter and the depositional environment.

Detrital organic matter is the nonliving remains of organisms found in sediments, soils, and water. It is comprised of organic molecules often in complex, macromolecular form. The initial source of all complex organic matter is photosynthesis whereby inorganic carbon is fixed by autotrophs. Higher plants, marine or lacustrine algae, or microbes are the dominant primary producers. Once carbon is fixed, that is, reduced to organic molecules by autotrophs, it is a valuable energy source. Heterotrophs consume this organic matter whether living or dead and derive energy from oxidizing it while converting a portion of it to their own biomass. In this process, the composition of the portion of that carbon that is utilized for biosynthesis is modified. Consequently, the composition of the organic matter changes between its initial fixation by autotrophs, through secondary biosynthesis by heterotrophs. Multiple transformations often occur before and during deposition in sediment and soil. Multicellular organisms consume living or nonliving particulate organic matter (POM) and excrete waste, but in aquatic and marine settings, microbes such as bacteria (and others such as Achaea) also utilize dissolved organic matter (DOM) excreted by phytoplankton or released by cell rupture and feeding of heterotrophs. Dissolved organic matter also enters these systems through leaching of soil organic matter. Dissolved organic matter in particular is also subject to nonbiologically mediated reactions such as photodegradation (Blough and Del Vecchio 2002; Del Vecchio and Blough 2002). Despite all the alterations of organic matter along the pathway from production to preservation, many organic compounds still reflect their origins.

Composition of Detrital Organic Matter
Understanding the chemical composition of the sources of organic matter is useful because these can be related to the organic matter preserved in depositional environments and ultimately the sediment record. Collectively, nonliving
organic matter in the environment, also referred to as detrital organic matter, is made up of the major biochemicals, protein, carbohydrates, and lipids. Proteins, composed of amino acids, contain most of the organic nitrogen in detrital matter. Carbohydrates are aliphatic compounds composed from simple sugar units and are used as storage molecules and structural materials. Cellulose is the main structural polysaccharide in higher plants. Lipids are composed of a wide range of compounds ranging from fats and waxes to alcohols and oils, and they also include steroids and hydrocarbons. Lignins are structural lipid molecules found in vascular plants that are used in cellular walls and these make up a significant proportion of the biomass particularly in woody plants. Cellulose and lignin are broken down by fungi and other microbes into their constituent units that are found in detrital matter. What distinguishes lipids in detrital organic matter from amino acids and carbohydrates is that amino acids and carbohydrates have structures that are largely ubiquitous among organisms. In contrast lipids, because of their range of distinct structures and the fact that they are preserved, means that even the modified and monomeric units serve as biomarkers for organic matter. This makes them useful for determining sources.

**Determining Sources of Organic Matter**

Lipids have widely varying reactivities as well as sources and structures. Lipid biomarkers, although a small portion of the total organic pool, have been successfully used to estimate the sources and reactivity of organic carbon in riverine and coastal systems (e.g., Alin et al. 2008; Drenzek et al. 2009; Goñi et al. 2008; Jaffé et al. 2006; Pearson et al. 2001; Sikes et al. 2009). Recalcitrant compounds, such as n-alkanes and n-alcohols, are widely distributed and well preserved in sediments, and their distribution of chain lengths have proven useful for source determination (Hermes and Sikes 2016; Meyers 1997; Oros and Simonet 2001; Prahl and Muehlhausen 1989). For example, the longer chain (C25–C31) n-alkanes are indicative of epicuticular leaf waxes (Eglington and Hamilton 1967; Kolattukudy 1976) and shorter chain lengths (C15–C25) come from aquatic and marine plants (e.g., Ficken et al. 2000; Jaffé et al. 2001).

The carbon isotopic composition of organic matter (δ13C) is a useful tool for distinguishing algal- from land-derived sources of organic matter in coastal environments because algal and vascular plants have distinct isotopic signatures (Jaffé et al. 2001; Kennicutt et al. 1987). Geochemical signatures of δ13C in organic matter have been used to indicate that there is dilution of land-derived POM by algal sources along estuaries (e.g., Benner 2004). Whereas combining biomarker with bulk δ13C analyses on particulate organic matter has improved the ability to differentiate sources in these complex environments (e.g., Canuel and Hardison 2016; Sikes et al. 2009). Combining biomarkers with compound specific isotopes and/or multiple isotopes analyses exploits the chemical and isotopic differences among terrestrial vegetation, marine algae, and bacteria. The δ13C of a biomarker can help constrain its origin. This has proven extremely effective for determining organic carbon sources and uptake in complex coastal systems (e.g., Canuel and Hardison 2016; Canuel and Martens 1996; Goñi et al. 2008; Sikes et al. 2009).

Optical properties (absorbance and fluorescence) have proven to be extremely useful tools for interrogating the composition of dissolved organic carbon in freshwater and marine systems (Cory and McKnight 2005; Jaffé et al. 2008; Komada et al. 2002; Stedmon et al. 2007). Advanced 3D excitation-emission matrix fluorescence spectroscopy (EEMs) is a nondestructive technique that distinguishes terrestrial and marine components, as well as aromatic and protein-like components in dissolved organic carbon (e.g., Coble 2007; Fellman et al. 2010).

**Transformation of Organic Matter Across the Terrestrial-Ocean Transition**

Export of organic carbon by rivers is positively related to the yield of suspended sediment, meaning that POM export is mostly controlled by physical erosion (Galy et al. 2015; Lyons et al. 2002). Globally ½ to ¾ of the terrestrial organic matter delivered to the ocean is remineralized along continental margins (Buridge 2005). Of the terrestrial organic matter that survives and makes it to the marine environment, ~90% of is buried in slope and shelf sediments with about 50%, focused into deltaic depocenters (Berner 1982; Blair and Aller 2012; Burdige 2005; Hedges and Keil 1995). The storage of organic carbon in terrestrial environments before delivery to the coastal ocean results in the common occurrence of pre-aged organic carbon in continental margin surface sediments (Bao et al. 2016). The mineral matrices are typically invoked as the primary mode of stabilization and sequestration of organic matter in sediments (Keil et al. 1994; Kennedy and Wagner 2011). This organic matter can be subject to further resuspension-deposition during which it is modified (Sun et al. 2002) and ages further (Bao et al. 2016).

The land-ocean interface and the coastal ocean are tremendously variable and dynamic. The rates of organic carbon burial and oxidation are influenced by terrigenous inputs, sediment transport processes, depositional conditions, oxygen levels, and marine productivity with these processes occurring over broad spatial and temporal scales (Bauer et al. 2013; Bianchi et al. 2016) Figure 1. Anthropogenic impacts that affect watersheds also impact the coastal ocean and these influences can cause coastal eutrophication and changes in the
supply of terrestrial sediment. Eutrophication drives bottom-
water hypoxia, the areas of which have expanded during the
twentieth century (Altieri and Gedan 2015). The change to
greater anoxia has largely increased the preservation of
organic carbon in estuaries and continental shelves (Bauer

An important conduit for terrestrial organic carbon to the
coastal ocean is through estuaries. Estuaries are recognized
as a complex component of the global carbon cycle that
regulate the delivery of land-derived sediment and transform
the amount and composition of organic carbon from rivers
through a wide array of degradation processes (Figure 1). By
being productive in their own right, estuaries add a complex
mix of marine and marsh derived organic matter to the system
(Abril et al. 2002; Bruesewitz et al. 2013; Canuel and
Zimmerman 2006; Cole et al. 2007; Hermes and Sikes
2016; Mannino and Harvey 2000; Medeiros et al. 2012).
The biogeochemical fate of organic matter in estuaries
remains poorly quantified leading to continuing uncertainty
with respect to the role of estuaries and coastal oceans in
regulating atmospheric CO₂ (Bauer et al. 2013).

The transformation of organic matter can be biologically
mediated or abiotic. For example, photooxidation alters
and removes DOM from surface waters (Figure 2) (Amon
and Benner 1996; Benner and Opsahl 2001; Gossior et al.
2009; Helms et al. 2013) and studies show that terrestrial and
plankton-derived organic carbon exhibit different degrees of
photochemical lability (Hernes and Benner 2003; Obernosterer
and Benner 2004; Rontani et al. 2012). Microbial degradation
consumes both dissolved and particulate organic matter and this process is also a source of modified organic matter (Figure 2) (Arnosti 2011; Komada et al.
2002; McCallister et al. 2004; Sun et al. 2002; Tremblay et al.
2007; Ziervogel and Arnosti 2009; Zimmerman and Canuel
2001). Notably, the interaction of biotic and abiotic trans-
formations can affect organic carbon reactivity. The concept
of priming – that fresh, labile carbon may enhance the reac-
tivity of semi-labile and recalcitrant carbon – has long existed
in the soils literature (Bingeman et al. 1953; Hamer et al.
2004; Kuzyakov et al. 2000) and has recently been advocated
as an important factor in the degradation of terrestrial organic
carbon in aquatic and marine systems (Aller and Blair 2006;
Bianchi 2011; Blair and Aller 2012).

Overall, the biogeochemical transformation of organic
matter as it moves from terrestrial source to marine sink
remains only roughly characterized. Characterization requires
multiproxy approaches that combine multi-isotopic and biomarker techniques (Blair et al. 2004; Goñi et al. 1997, 1998, 2006, 2008; Gordon and Goñi 2003; McCallister and del Giorgio 2008; Onstad et al. 2000; Sikes et al. 2009). Riverine multitracer studies have demonstrated that preaged terrestrial and recycled fossil organic matter is a significant component of the carbon mobilized and delivered to marine sediments (e.g., Drenzek et al. 2007, 2009; Goñi et al. 1997, 2006, 2008; Leithold et al. 2006; Pearson and Eglinton 2000; Pearson et al. 2001). Bulk organic carbon stable isotope and radiocarbon compositions reveal the diversity and complexity characteristic of organic carbon buried in marginal seas. This primarily relates to differences in marine and terrestrial inputs, the composition of the terrestrial component (e.g., vascular plant OM, soil, and petrogenic OM inputs), and processes modulating the fate of organic carbon within the marine environment (e.g., priming). This widely contrasting behavior of OM among these systems illustrates that the reactivity of organic carbon is a product of its chemical composition and regional conditions (Bianchi et al. 2017).

**Fate of Organic Matter: The Ocean**

The source and make-up of organic matter influences the fate of organic carbon in soils as well as marine sediments. Several mechanisms suggested to be responsible for the preservation are based upon the assumption that preservation, i.e., persistence, is related to chemical structure and physical environment. (1) Recalcitrant organic matter may occur as biologically produced resistant macromolecules such as lignin, peptidoglycan, algenans, or pyrogenic carbon (Dickens et al. 2004) which may be selectively preserved within soils and sediments. (2) Rapid burial spatially protects organic matter from decomposition via reduced access to microorganisms, and their hydrolyzing enzymes, and restricts diffusion of oxygen reducing aerobic decomposition. (3) The redox state of the environment is a fundamental control with preservation in anoxic environments substantially higher than in oxic environments. In the open ocean, about 90% of the organic matter produced by phytoplankton in the surface photic zone is consumed by zooplankton and microbial heterotrophs leaving only a few percent to sink out as particulate matter which in turn is further altered and consumed as it falls through the water column affecting the quality and reducing the quantity that finally reaches the depositional environment of the deep sea floor (Lee and Wakeham 1988). As particulate matter sinks, heterotrophic activity preferentially removes the more labile compounds such as proteins and carbohydrates and the remaining fraction becomes more refractory and enriched in lipids such as sterols and long chain alkanes and alkenones (Wakeham and Lee 1993). Overall the fraction organic carbon that can be identified as the major biochemicals diminishes with time in favor of macromolecular composites such as humic substances and kerogen which comprise most of sedimentary organic matter (Hatcher et al. 1983; Hedges et al. 2000).

In general, there is a correspondence between the amount of organic matter in the sediments, the overlying productivity, and the rate of sedimentation (Emerson 1985). Reactivity of organic matter is conditional. Organic material may be reactive in one environment, such as aerobic soils, but relatively stable in another such as in anoxic sediments. The role of oxygen in controlling both the amount and type of preservation the sediments is fundamental with the length of oxygen–exposure time being an important controlling variable (Hartnett et al. 1998). In all likelihood, there is a continuum of reactivities defined by source materials and ecosystem properties (Bianchi et al. 2017; Blair and Aller 2012).

**Summary**

The fixation of organic matter converts CO2 to reduced carbon removing it from the atmosphere and marine environment. The breakdown, and eventual remineralization back to CO2 of this OM are important processes within the global carbon and oxygen cycles. Natural organic matter is the largest reactive reservoir of reduced carbon on Earth. If we consider autotrophy the initial source of all organics, then the ocean and its sedimentary environments are the ultimate sink. Knowledge of the diverse sources of organics outstrips our understanding of the complex interactions of detrital organics within the global carbon cycle. In particular, the carbon cycle of the coastal ocean is a dynamic component of the global carbon budget that remains poorly understood. Understanding the alteration of organic material flowing from rivers to the ocean and carbon fluxes within and between coastal sub-systems is becoming an increasing area of research over the past few decades because the alteration by climate and anthropogenic changes within these systems are substantial. Understanding and accurately accounting for the factors regulating the organic and inorganic carbon fluxes between and within terrestrial and marine systems is important for achieving closure of the global carbon budget (Figure 1).

**Cross-References**

- Biogeochemistry
- Biomarkers: Coal
- Biomarkers: Petroleum
- Carbon Cycle
- Carbon Isotopes
- Dissolved Organic Carbon
- Kerogen
- Organic Facies
- Organic Geochemistry
- Organic Matter Degradation and Preservation


