Introduction

Terrigenous sediments are the weathering products of rocks exposed at the Earth’s surface. They are brought to the ocean by rivers, winds, and ice and may be redistributed in the ocean by currents. Accordingly, variations in composition, grain size, and flux of terrigenous marine sediments hold clues to important paleoclimate variables such as wind speed and direction, aridity, glacial activity, and ocean currents. This article gives an overview that outlines the potential of terrigenous sediments in paleoceanography applications, specifically concerning their provenance (sources), weathering history, sorting (grain size distribution), and flux (see Paleoceanography).

Away from continental slopes, clay minerals are the most widely distributed terrigenous components in pelagic marine sediments, and their occurrence and distribution is well reviewed by Kennett (1982) (see Eolian Records, Deep-Sea Sediments). Some clays are formed as weathering or alteration products of primary silicate minerals, and others are recycled from sedimentary sources. All clay minerals are very fine-grained due to their crystal structure. Four types of clays are dominantly found in marine sediments: chlorite, illite, kaolinite, and smectite. In most cases, chlorite and illite are primary minerals from the source, while kaolinite and smectite are newly formed alteration products. Mineral composition of the clays is related to a number of factors, including source rock type and weathering. Weathering in turn is controlled by relief, temperature, precipitation, and vegetation, and consequently, the different kinds of clay reflect the major soil types in the source areas (Gibbs, 1967). Most clays are carried to the ocean and deposited without being changed, and thus marine sediments contain clays that reflect the weathering process that produced them (e.g., Biscaye, 1965). Primary minerals such as chlorite and illite are relatively more abundant in colder climates, while kaolinite is characteristic of tropical zones (Fig. 1). Smectite tends to be associated with distribution of volcanic sources. Although substantially more sediment is transported to the ocean by rivers than winds, most is retained near margins. Thus, most of the clays deposited in areas far away from the continents are delivered by winds (Kennett, 1982, Rea and Hovan, 1995, see also review in Kohfeld and Harrison, 2001), particularly in the Pacific Ocean. Additionally, clay distribution is also related to ocean current distribution, both surface and deep (e.g., Kennett, 1982, Petschick et al., 1996, Franzese et al. (submitted)).

Although clay minerals are the dominant terrigenous component of the abyssal plains, in polar and subpolar regions, melting icebergs may contribute a significant amount of coarse sediment, called ice-rafted detritus (IRD) (see Glacimarine Sediments and Ice-Rafted Debris). IRD is composed of a large spectrum of grain sizes, ranging from clay to sand and gravel, but its presence is identified in marine sediments by the coarse fraction because rafting is the only means of delivering coarse sediment to these regions (e.g., Ruddiman, 1977). The recognition of IRD allows paleoceanographers to study ice-sheet dynamics in the past, and its distribution indicates the flow of surface currents that carried the icebergs (Fig. 2).

Provenance and Process and the Application of Terrigenous Sediments in Paleoceanography Research

To identify approaches for characterizing sediment provenance, it is important to consider which parameters are more prone to preserving signals of sedimentary processes such as weathering and sediment transport versus those that are likely to look beyond sedimentary processes to yield insights into the crystalline source composition. For the purpose of using the terrigenous fraction of marine sediments for paleoceanography/paleoclimate applications, weathering is an important parameter to constrain. Additionally, it should be noted that weathering and sorting history are distinguished as processes in this treatment because they are part of the sedimentary processes, but the entire compositional constraints include provenance characteristics, and likewise all the compositional variations are controlled by processes: igneous, metamorphic, and sedimentary. In the following, some tools to constrain sedimentary provenance and process are reviewed, followed by a brief review of sedimentary processes, and finally, an overview of terrane types or provenance components.

Tools

Mineralogy

Mineralogy by X-ray diffraction (XRD) provides important information on and weathering history of
marine sediments (e.g., Biscaye (1965)). For example, the kaolinite/chlorite of the <2 μm fraction of surface sediments from the Atlantic Ocean gives an important first-order view of the sources and processes responsible for distributing sediments in the ocean (Fig. 1). Mineralogy by XRD has become a widely used tool in paleoceanography to constrain weathering intensity as well as sources and transportation pathways.

Geographic variations in mineralogy can help to constrain sediment transportation processes. For example, Petschick et al. (1996) made a more detailed map of the clay mineral distribution in the South Atlantic Ocean than the one from Biscaye (1965). The summary map from Petschick et al. (1996) is shown in Figure 3A, along with surface contributions and deep current systems. An example of inherited ‘tropical’ signal is seen in the kaolinite-rich zone near the Filchner-Ronne Ice shelf. Although deep currents represent an important means of transporting sediment, for example, the tongue of chlorite-rich sediment in the western South Atlantic along the South American margin, comparison of the clay province boundaries with the distribution of surface currents in the South Atlantic (Fig. 3B), the bathymetry of the South Atlantic (Fig. 3C), and the July and January average winds (Figs. 3D and E), it becomes clear that surface currents (and/or the winds that drive them) are also responsible for the first-order distribution of terrigenous sediments in the South Atlantic. Further support for the importance of surface currents for distributing sediments from long-distance

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**Figure 1** Map of kaolinite/chlorite distribution of the <2 μm terrigenous fraction of sediments from the Atlantic Ocean. Modified from Biscaye PE (1965) Mineralogy and sedimentation of recent deep-sea clay in Atlantic Ocean and adjacent seas and oceans. *Geological Society of America Bulletin* 76: 803.
X-Ray Fluorescence

X-ray fluorescence scanners are part of emerging technology that allows rapid semiquantitative determination of elemental concentrations in marine sediments at resolutions down to 100 μm. This has important implications for high-resolution surveying of marine sediment cores. An important example is the recognition of greatly increased flux of terrigenous sediments based on the Fe/Ca ratio of sediments from the Brazil margin, at the approximate times of Heinrich Events (massive iceberg events in the North Atlantic), that correlated to rapid climate variability in many parts of the world (Arz et al., 1998; Hemming, 2004). Another fundamental example is the correlation of Ti concentrations, as a proxy for rainfall in the Cariaco Basin, with collapse of the Mayan civilization (Haug et al., 2003) used terrigenous sediment compositions to evaluate variations in rainfall in the source areas to the Cariaco Basin, South America. In this case, the bulk titanium content of undisturbed sediment reflects variations in riverine input and the hydrological cycle over northern tropical South America. This is significant because it ties drought to the collapse of the Mayan civilization.

Petrography

Petrography studies allow identification of major lithological components in the sand fraction, as well as potentially diagnostic minerals and/or rock types. This approach has been particularly useful for identifying sources of IRD in the ocean. For example, it was the first line of evidence used to infer the importance of Hudson Strait sources to the Heinrich layers, layers rich in IRD in the North Atlantic associated with major abrupt climate change (Bond et al., 1992), reviewed in Hemming (2004). It was also used by Bond and Lotti (1995), as well as others afterwards, to examine the relative timing of different iceberg contributors in the North Atlantic. Petrographic studies of IRD can sometimes be used to identify IRD from specific ice sheets and thus be used to make inferences about the behavior of specific ice sheets during times of climate change, and can also be used to trace the average path of the main surface currents in regions where icebergs and sea ice are produced.

Geochemical Approaches to Terrigenous Sediment Provenance

Geochemical approaches, including isotopes, complement information inferred from mineralogical investigations. Although the composition of organic matter from terrigenous sources is acknowledged as a powerful provenance tracer, only the silicate portion of these sediments is reviewed here. Geochemical approaches to the silicate portion of terrigenous sediments allow us to

transport comes from the emerging work of Franzese et al. (submitted), that makes a compelling case for the importance of the Agulhas Current as a key pathway for sediment transport around the tip of Africa.
constrain provenance age and geochemical history of the source as well as the weathering history. As described by McLennan et al. (1993), among the important geochemical characteristics that define fundamental provenance types are radiogenic isotope compositions (reflecting average provenance age), large-ion lithophile element enrichments, and other trace element characteristics such as Europium anomalies (reflecting provenance compositions), alkali and alkaline earth element depletions and aluminum enrichment (reflecting weathering and alteration), Zr and Hf enrichments (reflecting increased concentration of zircon by sedimentary sorting), and high Cr abundances (indicating ultramafic sources).
Radiogenic Isotope Provenance Tracers

The commonality in these is that they are the radioactive decay products of parents with long half-lives. They have different sensitivities depending on the different geochemical behaviors of the parents and daughters, and on the rock types and geological history of the sources. Thus, they provide provenance constraints that are related to both the age and time-averaged geochemical characteristics of sedimentary sources. The most widely used for constraining the provenance of terrigenous marine sediments are the Sm–Nd and Rb–Sr systems (e.g., Dasch (1969), Goldstein et al. (1984), Grousset et al. (1988), Jones et al. (1994), Grousset and Biscaye (2005), and Franzese et al. (submitted)). Although less widely used to date, the U–Th–Pb, Lu–Hf, and K–Ar systems have also been shown to provide powerful provenance constraints. The Sm–Nd isotope system provides an average age of crust formation of the sediment’s sources (Goldstein et al., 1984). As reviewed by Taylor and McLennan (1985), this is because Sm and Nd are rare earth elements with similar radii, and thus are generally not separated by most sedimentary processes (although there are exceptions). A compelling example of the utility of Nd isotopes for tracing sediment sources in the North Pacific is shown in Figure 4, where the eolian contribution from China dominates the sediments’ provenance in the center of the North Pacific.

Although there is a gross negative correlation between Nd and Sr isotopes in terrigenous sediments (Fig. 5), the Rb–Sr isotope system may be disturbed by many geological processes (Dasch, 1969; Goldstein and Jacobsen, 1988) and thus provides a wide range of compositions for a given Sm–Nd model age or $\varepsilon_{Nd}$. This is because of the large geochemical difference between Rb (alkali metal) and Sr (alkaline earth element) as well as their mineralogical hosts. In addition to the sedimentary alteration of the Rb–Sr system described below, metamorphism tends to break down and reform the mineral hosts of these elements, and thus metamorphic resetting of the Rb–Sr isotope system is common. Accordingly, the Rb–Sr isotope system provides a large signal compared to our ability to measure the Sr isotope composition.

Constant Flux Proxies

These provide important constraints on sedimentary redistribution in the ocean. Examples are $^{230}$Thxs (derived from radioactive decay of $^{234}$U in the water column, e.g., Bacon (1984), Henderson and Anderson (2003)) and $^{3}$He (derived from interplanetary dust particles, e.g., Ozima et al. (1984)). $^{230}$Th is a constant flux proxy because thorium is highly particle reactive, and thus it is quickly removed from the water column after forming by radioactive decay of $^{234}$U which uniformly produces $^{230}$Th in the water column at a known and constant rate. The $^{3}$He content of marine sediments is a constant flux proxy because interplanetary dust particles rain to the earth at approximately constant rates and they have extremely high $^{3}$He contents. Thus they act like an isotope spike. The
enhancement of sedimentation rate by advection is well-known on drift deposits, for example, Bermuda Rise. In fact, they are favored sites for paleoceanography research due to the high accumulation rates that provide great temporal resolution. This process is termed ‘focusing,’ and the ‘focusing factor’ is the ratio of accumulation rate from chronology to accumulation rate that would hold if only sediment settling vertically through the water column above the deposition site were deposited. However, geochemical proxies for constant flux have identified additional sites where the sediment morphology does not clearly indicate drift deposits, yet the vertical accumulation of sediments based on chronology of the sediments is greater than that estimated from the concentrations of constant flux proxies in the sediment. Reconciling diverse interpretations of paleoproductivity changes and terrigenous contributions to iron-fertilization, for example, in the eastern equatorial Pacific (e.g., Murray et al. (1995), Paytan et al. (1996), Marcantonio et al. (2001), Loubere et al. (2004), Paytan et al. (2004), Francois et al. (2004), Anderson and Winckler (2005), Lyle et al. (2005), Anderson et al. (2006)), is expected to yield important insights into marine sedimentary processes.

Grain Size Distributions

These can provide compelling information about the transporting agent (wind, water, ice) as well as the velocity of wind and water. For example, wind tends to carry fine-grained sediments, with average grain size decreasing with distance from source (e.g., Rea (1994)). Bottom currents act to move sediments their paths along shaped by bathymetric boundaries. Drift deposits accumulate in association with the movement of these deep water boundary currents. An example in which mineralogy elucidates the movement of sediments along the Western Boundary Undercurrent in the North Atlantic comes from the eastern Labrador Sea (e.g., Fagel et al. (2001)).
scientists have shown the dispersion of smectite from volcanic sources associated with the Icelandic hot spot into the Labrador Sea, with maximum concentration at the depth of the Western Boundary Undercurrent. Bottom currents tend to enrich drift deposits in sortable silt, grain sizes between 10 and 63 μm (e.g., Bianchi and McCave (2000)), with the mean sortable silt grain size being proportional to current velocity and thus an important measure of bottom currents’ relationship to climate variability (e.g., Hall et al. (1998), Bianchi and McCave (1999)). Weltje and Prinz (2003) have showed that a combined approach of grain size and compositional variability with inverse, end-member modeling allows de-convolving source and process controls in terrigenous marine sediments.

**Sedimentary Processes**

**Weathering**

Predictable bulk chemical changes occur during weathering, and the Chemical Index of Alteration (CIA) has been established as a general guide to the degree of weathering (Nesbitt and Young, 1982). Using molecular proportions (and only considering CaO residing in silicate minerals rather than in phosphate and carbonate):

\[
\text{CIA} = 100 \ast \frac{\text{Al}_2\text{O}_3}{\text{Al}_2\text{O}_3 + \text{K}_2\text{O} + \text{Na}_2\text{O} + \text{CaO}}
\]

For marine sediments it is also necessary to make a correction on Na₂O for seawater salt (e.g., McLennan et al. (1990)). On the CIA scale, unweathered igneous rocks have values of 50 or slightly below, while the most extreme residual clays have values of almost 100. Typical shales average about 70–75 (Fig. 6). The bulk-rock chemistry is dominated by the conversion of feldspars or glass to clay minerals during weathering.

The contents of some trace elements in sediments are different from those of their sources due to sedimentary processes of weathering and sorting, and measurement of these may provide clues about the processes and pathways of sediment distribution. For example, during weathering, there is a substantial increase in the Rb/Sr ratio of most solid residues (e.g., Dasch (1969)). Rb tends to follow K and is enriched in K-feldspar and micas, whereas Sr tends to follow Ca and is enriched in plagioclase and pyroxene. Plagioclase and pyroxene are generally susceptible to chemical attack during weathering, and Sr is removed to the aqueous system. Rubidium’s hosts have greater resistance to chemical weathering and additionally, Rb released during weathering tends to follow Al and thus be retained in the solid system. This is because Rb⁺, a large alkali trace element, is more readily retained on exchange sites of clays that the smaller alkaline earth element, Sr²⁺. Thus, terrigenous sediments that are derived from highly weathered terrains and/or sedimentary sources will tend to have high Rb/Sr ratios. Recent enrichments in Rb relative to Sr will result in lower ⁸⁷Sr/⁸⁶Sr and thus younger Rb–Sr model ages, so in favorable cases it is possible to distinguish recent weathering from sedimentary sources in terrigenous marine sediments.

The K₂O/Na₂O and K₂O/CaO of solid residues of weathering are also increased. Additionally, the K/Ar system may be almost entirely reset during extreme weathering. This is because K⁺ is retained on exchange sites of clays, analogous to Rb⁺, and Ar is a noble gas that is released to the atmosphere during the breakdown of feldspar. Accordingly, the CAI, Rb–Sr and K–Ar systems are complementary approaches to study time-integrated weathering effects on terrigenous sediments. The fact that much illite is brought to the ocean as a primary mineral is supported by the survey of K/Ar ages by Hurley et al. (1963).

**Sorting**

Sorting also tends to separate denser minerals from the bulk sediment, and elements like Zr and Hf, that are enriched in the heavy mineral zircon (ZrSiO₄), aid in identifying extreme sorting effects in sediments (e.g., McLennan et al. (1990)). For example, McLennan et al. (1990, 1993) showed that it is possible to isolate source compositional variability from sedimentary sorting by plotting Th/Sc versus Zr/Sc (Fig. 7). Th/Sc is not influenced appreciably by sorting, but is highly
-sensitive to compositional variability of the source because Th is incompatible while Sc is moderately compatible during melting and crystallization of magmas. Zr and Hf are enriched in the heavy mineral fraction of sediments, particularly in zircon, which is among the most robust minerals, surviving multiple sedimentary cycles, as well as high-grade metamorphism and even melting. Sorting may also separate Rb from Sr. Clay fractions will generally contain higher Rb/Sr than the coarse fractions. This can be conceived simply by considering the main host of Rb and Sr in the clay fraction to be illite and in the silt and sand fractions to be feldspar. In a first order there is a separation of these elements according to mineralogy such that Rb is mostly found in mica and Sr is mostly found in feldspar. This is the reason there tends to be higher 87Rb/86Sr in clays compared to sands.

**Terrane Types or Provenance Components**

For most practical purposes there are no unique ways of identifying or ‘fingerprinting’ sediment sources, and it is useful to group sediment provenance characteristic into terrane types. McLennan *et al.* (1990, 1993) have done this with the goal of expanding our ability to understand tectonic settings from ancient sediment compositions. The groupings used by these authors are also useful in considering provenance components in modern or young terrigenous marine sediments in the pelagic realm, and they are (1) old upper continental crust, (2) recycled sedimentary rocks, (3) young undifferentiated arc, (4) young differentiated arc, and (5) exotic components. A sixth component that may be a significant portion of the terrigenous marine sediments in the pelagic realm, and away from continental inputs (e.g., in the Antarctic Circumpolar current, downstream from oceanic plateaus and ridges) is (6) oceanic basalt.

Continental crust is distinguished from undifferentiated sources (arc and oceanic basalt) by evolved major element compositions (e.g., high SiO$_2$/Al$_2$O$_3$ and K$_2$O/Na$_2$O), negative Eu anomalies, and enrichments of normally incompatible over compatible trace elements. For example, continental crust yields sediments with light rare earth element enrichment, high Th/Sr and high La/Sc.

Sediments derived from old upper continental crust tend to have a substantial component of recycled sedimentary rocks in their provenance. In addition to the characteristics generally noted for continental crust, sediments derived from old continental crust will tend to have high Rb/Sr and high Th/U reflecting weathering and sedimentary recycling. The presence of old continental sources is most simply identified by radiogenic isotope analyses.

Recycled sedimentary rocks are a common and important contributor to terrigenous sediments, and it is difficult to distinguish ambient weathering from recycled sedimentary sources. Measurements such as K/Ar ages, Rb/Sr model ages, and clay mineralogy are probably the best ways to distinguish these in young terrigenous sediments.

Young undifferentiated arc sources are recently derived from the mantle without significant intracrustal differentiation. This provenance component has many attributes in common with oceanic basalt sources but may have different implications for sedimentary (and thus paleoclimate/paleoceanography) applications. In Quaternary applications, the distribution of possible sources is largely still available for study, and the geographic pattern of variation in provenance helps to distinguish these contributions. Compared to continental sources they provide sediments with less evolved major element compositions (e.g., low but variable SiO$_2$/Al$_2$O$_3$ and K$_2$O/Na$_2$O), absence of negative Eu anomalies, and little enrichments of normally incompatible over compatible trace elements, so they have low Th/Sr and La/Sc.
ratios. They also tend to be less weathered and have a smaller recycled sedimentary component, so their CIA and Rb/Sr are low.

Young differentiated arc sources have very similar characteristics to continental crust, and can be thought of as young continental crust. In most cases these sources also tend to be less weathered than old continental sources, with a smaller recycled sedimentary component, so their CIA and Rb/Sr are low.

In specific cases, identification of even miniscule amounts of certain exotic components can have very important application. McLennan et al. (1993) cite published examples of their utility for constraining the timing of approach of allochthonous terranes as well as identifying ocean crust components in modern forearc turbidites. If identified, exotic components can provide near-unique information for interpreting provenance of terrigenous sediments in Quaternary settings.

See also: Glacial Landforms, Sediments: Glacimarine Sediments and Ice-Rafted Debris. K/Ar and Ar/Ar Dating. Periglacial Landforms, Rock Forms: Rock Weathering.

References


**PALEOCEANOGRAPHY, RECORDS**

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**Introduction**

During the last 3 Myr, the climate of the Earth has been marked by a succession of large glacial–interglacial changes which shaped the relief of the Earth and eventually led toward modern biodiversity. Oceanic sedimentary sequences provide the most continuous records of these dramatic variations and offer a complementary view of continental records. Among the oceanic indicators of past climatic changes, the oxygen isotope composition of foraminifera in deep-sea cores, as a proxy of past changes in global ice volume, has been one of the most insightful tools revealing the history of continental ice sheets. The most striking result of paleoceanographic studies using the δ18O was the discovery of periodic glacial–interglacial successions, which were paced by the orbital forcing as theorized by Milankovitch. Whereas the late Pleistocene spectrum is mainly marked by the 100 kyr cycle, the succession of glacial and interglacial periods during the early Pleistocene – from 1.8 to about 0.8 Ma was marked by a very regular cycle of 41 kyr. Moreover, oxygen isotope records showed that within the same interval, the buildup of ice caps in the high latitudes during ice ages was considerably smaller during the early Pleistocene than later. The global distribution of continents during the early Pleistocene was not significantly different than during the late Pleistocene, eliminating changing geography as a mechanism for the Pleistocene climate evolution. The 41 kyr ‘world’ of the early Pleistocene is thus a key period of Earth’s history when global climate changed toward modern climate without any strong external force effecting changes, and the study of this interval