Collaborative Research: Management and Implementation of US GEOTRACES Pacific Meridional Transect

PROJECT SUMMARY

Overview: GEOTRACES investigators use high spatial resolution sampling and simultaneous measurements of trace elements and isotopes (TEIs) and hydrography on ocean basin sections to examine source fluxes and biogeochemical processes affecting TEIs. This proposal seeks to fund the essential sampling operations and infrastructure for the US GEOTRACES Pacific Meridional Transect along 152° W (GP15) to support a large variety of individual science projects on TEI biogeochemistry that will follow. Thus, the major objectives of this “management” proposal are: (1) plan and coordinate a 60 day research cruise in 2018; (2) obtain representative samples for a wide variety of TEIs using a conventional CTD/rosette, GEOTRACES Trace Element Sampling Systems, and in situ pumps; (3) acquire “conventional” CTD hydrographic data along with discrete samples for salinity, dissolved oxygen, algal pigments, and dissolved nutrients at micro- and nanomolar levels; (4) ensure that proper QA/QC protocols are followed and reported, as well as fulfilling all GEOTRACES intercalibration protocols; (5) prepare and deliver all hydrographic data to the GEOTRACES Data Assembly Centre (via the US BCO-DMO data center); and (6) coordinate all cruise communications between investigators, including preparation of a hydrographic report/publication. These objectives mirror those in the preceding US GEOTRACES transects that have resulted in high quality data for use by the marine biogeochemistry and modeling communities, and rapid advances in our understanding of TEIs in the ocean system.

Intellectual Merit: The fact that many trace elements are bioactive and essential (e.g., Fe, Zn), or toxic (e.g., As, Hg), underlies interest in studying them, but their effects on primary production and oceanic carbon dioxide uptake are the primary drivers. In parallel, many radioactive and stable isotopic tracers allow trace element sources to be identified (e.g., ^{3}He, ^{56}Fe) and rates of transformation or fluxes determined (e.g., ^{230}Th, ^{228}Ra, ^{15}N and $\delta^{13}C$). GEOTRACES use of multi-element, high-resolution sampling, coupled with various modeling approaches, allow the inputs/sources and internal cycling of TEIs to be revealed and quantified in an unprecedented fashion. A meridional transect in the central Pacific basin is very compelling since it would sample: strong margin fluxes, subarctic HNLC waters, the oldest deep water in the world’s oceans, the distal ends of hydrothermal plumes from the Juan de Fuca Ridge and East Pacific Rise as well as oxygen minimum zones, equatorial upwelling, and some of the most oligotrophic waters in the world’s oceans in the South Pacific gyre at 20°S. The cruise would also allow temporal variability to be addressed since it will be along the CLIVAR/Repeat Hydrography P16 line, and near existing time series stations and sites of previous TEI studies.

Broader Impacts: This meridional cruise will vastly improve our understanding of TEI cycling, including inputs, outputs and internal cycling. This work will provide TEI data to a broad scientific community through timely data sharing and meeting coordination. This project will also provide baseline measurements of TEIs in the Clarion-Clipperton fracture zone (~7.5°N-17°N, ~155°W-115°W) where large-scale deep sea mining is planned. Environmental impact assessments are underway in partnership with the mining industry, but the effect of mining activities on TEIs in the water column is one that could be uniquely assessed by the GEOTRACES community. GP15 is proposed to go through the western end of this zone in 2018, and provide baseline data before major mining activities commence. In terms of communicating our science to a larger audience, we will recruit an early career freelance science journalist with interests in marine science and oceanography to participate on the cruise and do public outreach, photography and/or videography, and social media from the ship, as well as to submit articles about the research to national media. In addition to a professional journalist on the cruise, there is a long tradition of student, postdoc, and technician blogs on US GEOTRACES cruises starting with the 2008 Intercalibration cruise, and we fully support these outreach activities in addition to our conventional means of communicating our science on University web sites and talks to local citizen groups like clubs and associations.

INTRODUCTION

Since the development of non-contaminating sampling systems and suitable analytical methods to detect them at nanomolar concentrations and below (e.g., Bruland et al., 1979), the interest in trace elements in the world's oceans has risen exponentially in the last 30 years. The fact that many of these elements are bioactive and essential (e.g., Fe, Sunda, 2012; Zn, Sinoir et al., 2011, Co, Saito, 2001) or toxic (e.g., As, Sanders, 1979; Cu, Brand et al., 1986) underlies this interest. The effects of trace elements on primary production and oceanic carbon dioxide uptake (Martin, 1990; Falkowski et al., 1998) are the primary drivers. In parallel, many radioactive and stable isotopic tracers allow trace element sources to be identified (e.g., ^{3}He, Lupton et al., 1977; ^{56}Fe, Conway and John, 2014) and rates of transformation or fluxes determined (e.g., ^{230}Th, Anderson et al., 1983; ^{228}Ra, Charette et al., 2016; ^{15}N and δ^{13}C Sigman and Haug, 2003; Altabet and Francois, 1994). Each trace element and isotope (collectively, TEIs) has its own relevance to biogeochemical processes in the ocean, and previous studies have focused on individual elements or processes (e.g., Hutchins et al., 1998; Moore and Doney, 2007). However, the international GEOTRACES program has developed and gathered the sampling, analytical, and data synthesis tools to examine a large suite of TEIs in parallel such that the total information gathered on an ocean basin's biogeochemistry is much greater than the sum of the parts (Anderson et al., 2014).

To study TEI cycling, GEOTRACES investigators use two complementary strategies: section cruises and process studies. On ocean basin sections, high spatial resolution and simultaneous measurements of the GEOTRACES TEIs and hydrography are conducted. This strategy allows source fluxes to be examined and many of the biogeochemical cycling processes to be revealed. Indeed, the types of amazing data sets generated through the GEOTRACES multi-element approach, based on international collaborations, are shown in the dissolved Fe and Zn 3-D distributions for the Atlantic Ocean (Figure 1, with data from section cruises by 4 different countries). While both Fe and Zn are essential elements, it is easy to visualize the different processes such as hydrothermal delivery of Fe and transport of Antarctic water masses with elevated Zn shaping their distributions. Superimposed upon these two input terms are uptake in surface waters and regeneration at depth. Simultaneous measurements of tracers like Th and Ra isotopes (not shown in Fig. 1) also allow rates of inputs, uptake, and export/regeneration to be computed, as well as identifying individual sources. The power of this multi-element, high-resolution sampling, combined with multiple modeling approaches, allow the inputs/sources and internal cycling of TEIs to be revealed and quantified in an unprecedented fashion; these sources and processes are depicted in Figure 2. A direct result of these section cruises is they can also reveal important mechanisms and ideal sites for more detailed process studies, the second GEOTRACES sampling strategy.

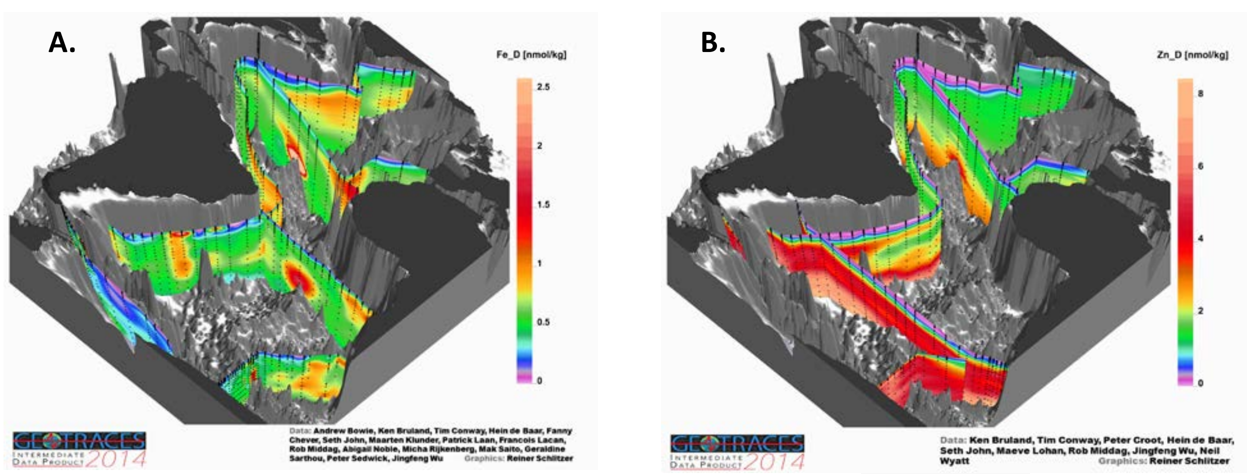


Figure 1. **A**. Dissolved iron and **B**. zinc distributions in the entire Atlantic Ocean (Schlitzer, 2015**.**).

To date, the US has conducted three GEOTRACES section cruises, the 2010-2011 North Atlantic Zonal Transect (NAZT), 2013 Eastern Pacific Zonal Transect (EPZT), and the 2015 Arctic study. This proposal seeks funding to conduct a meridional transect in the Pacific Ocean from 56°N to 20°S along 152°W that was planned at a US GEOTRACES Pacific Implementation workshop in 2008 (Moffett and German, 2009). Conducting a meridional transect in the central Pacific basin is compelling from the TEI standpoint since it would sample (going North to South): strong margin fluxes, subarctic HNLC waters, the oldest deep water in the world's oceans, the distal ends of hydrothermal plumes from the Juan de Fuca Ridge and East Pacific Rise as well as oxygen minimum zones, equatorial upwelling, and some of the most oligotrophic waters in the world's oceans in the South Pacific gyre at 20°S. This will be the first meridional section of the U.S. GEOTRACES program, and indeed, this transect would allow virtually all of the processes and fluxes in Fig. 2 to be examined by the participating scientists and laboratories. Moreover, it dovetails perfectly with the EPZT, linking TEIs and hydrography from a swath that essentially covers most of the NE Pacific (shown in greater detail below) as envisaged by the 2008 workshop (Moffett and German, 2009). As the core management component of the transect, this proposal is designed to provide the essential support and management structure for acquiring the TEI samples and hydrographic data needed by other investigators. Background information and justifications for this transect, and details on its implementation, will be elaborated in the sections to follow.

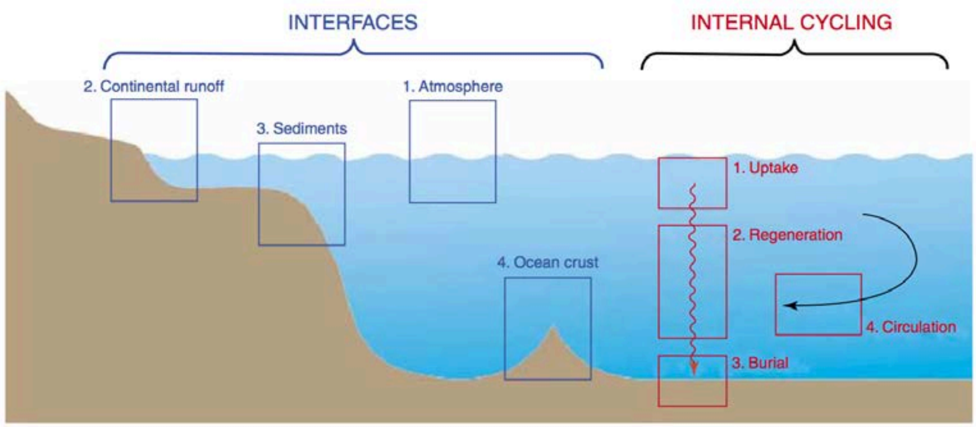


Figure 2. Flux interfaces and internal cycling for trace elements and isotopes (GEOTRACES, 2006).

BACKGROUND

Hydrography and circulation

The hydrography and circulation of the Pacific Ocean sets first order constraints on the distribution of trace elements and isotopes, from the cyclonic subpolar gyres that influence circulation to great depths (Talley et al., 2011) to complex zonal circulation near the equator. Here we outline a few key features of the circulation and their expected influence on TEI distributions along the proposed section.

Surface circulation in the upper 400 m

The westward flowing Alaskan Stream is the northern boundary of the cyclonic (counterclockwise) subpolar gyre, which is separated into the Western Subarctic Gyre and the Alaskan Gyre (Favorite et al., 1976). Where the Aleutian Island chain dips southward around 143°W, the Alaskan Stream forms a western boundary current for the Alaskan Gyre. The Gulf of Alaska coastal waters receive freshwater discharge from mountainous glaciers containing a high sediment load of fine glacial flour and highly reactive particulate iron (Lippiatt et al., 2010). Offshore transport of these coastal waters would be expected to be a major source of TEIs into the HNLC Alaskan Gyre.

The Subarctic Frontal zone (SAFZ; centered around 42°N) is the southern boundary of the subpolar gyre, and is embedded within the North Pacific Current, the broad eastward flow of the central and eastern subtropical gyre (Roden, 1991). The SAFZ is the boundary between higher productivity, subpolar waters to the north and low productivity, subtropical waters to the south. The SAFZ is itself a dynamic zone of intense primary productivity with extensive changes in phytoplankton community composition (Juranek et al., 2012). This front also marks the boundary between low salinity, upwelling waters to the north and higher salinity, downwelling waters to the south and is likely to mark a transition in the sources of TEIs from margin-dominated in subpolar waters to dust-dominated in subtropical waters. The center of the subtropical convergence is about 32°N, and while the subtropical gyre circulation extends to 1000 m in its center, there is rapid attenuation with increasing depth to the north and west (Reid, 1997). Low nutrient availability within the subtropical gyre leads to low productivity and low particle scavenging, and it provides a niche for nitrogen-fixing cyanobacteria, which have different elemental and trace metal stoichiometries compared to diatom-dominated subpolar ecosystems (Karl et al., 1997).

Equatorial waters are a complex "layer cake" of alternating eastward and westward flows (Figure 3; Talley et al., 2011). The North Equatorial Current (NEC) is the broad westward flow at the southern boundary of subtropical gyre (8-20°N). It is separated from its southern counterpart, the South Equatorial Current (SEC), by the eastward flowing North Equatorial Counter Current (NECC), centered around 5°N. The SEC extends from about 3°N to 10°S, and is fed by the Peru-Chile eastern boundary current. Easterly trade winds cause Ekman transport of surface SEC waters to the north and south of the equator, leading to equatorial upwelling from the thermocline. The equatorial portion of the SEC is confined to a thin layer above the Equatorial Undercurrent (EUC), and can disappear or reverse to eastward at the onset of an El Niño (Wyrtki, 1975). Below the NEC and SEC, which extend into the thermocline, the eastward flowing North and South Subsurface Counter Currents (NSCC and SSCC; Tsuchiya, 1972, 1975) transport salinity, oxygen, and nutrients characteristic of the western Pacific toward the east.

The EUC is one of the fastest permanent currents in the world, with an average speed of >90 cm/s at its core in the thermocline (Wyrtki and Kilonsky, 1984). The EUC is fed by the New Guinea Coastal Undercurrent, the northward western boundary current of the South Pacific gyre. This current sweeps the Papua New Guinea margins, tagging the EUC waters with distinct TEI signals, including elevated dissolved and particulate trace elements (Gordon et al., 1997; Slemons et al., 2010; Kaupp et al., 2011), and distinct rare earth element and isotopic imprints (Sholkovitz et al., 1999; Lacan and Jeandel, 2001), some of which are measurable into the central and eastern Equatorial Pacific. The EUC also plays an important role in ventilating the eastern tropical Pacific (Toggweiler et al., 1991), and sets background conditions of TEIs in water flowing into the oxygen minimum zones (OMZs). Establishing TEI signatures in this current will help interpret the local effects of OMZs on TEI distributions in the eastern Pacific.

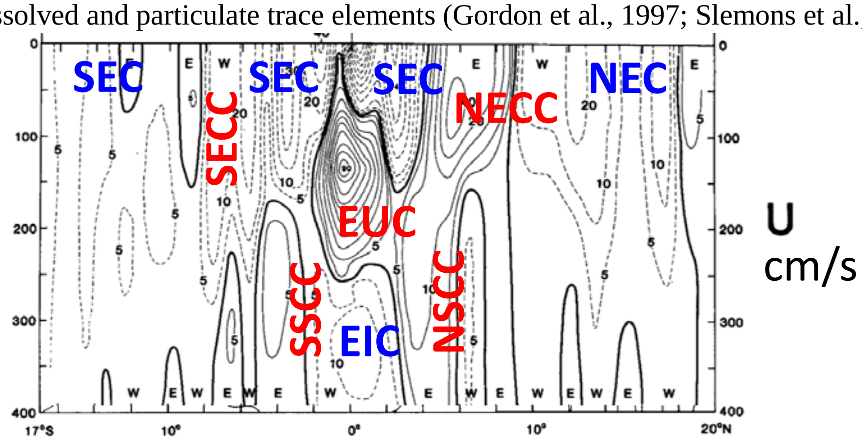


Figure 3. Zonal geostrophic flows along the Equator taken between 150-158°W (Wyrtki and Kilonsky 1984). Westward flows are labeled in blue, while eastward are labeled in red.

Intermediate waters

Intermediate waters in the Pacific derive from two main sources: Antarctic Intermediate Water (AAIW) in the south (Tally et al., 2011) and North Pacific Intermediate Water (NPIW) in the north (Talley, 1993). AAIW and NPIW both can be identified as minima in salinity (Figure 4A) and maxima in O_2 (Figure 4B) above 1000 m along P16. Their hydrographic and endmember TEI characteristics are set by their formation regions in the surface Subantarctic Mode Water layer just north of the Subantarctic Front, and in the Sea of Okhotsk and northwest Pacific, respectively. The flow at intermediate depths is largely dominated by the anticyclonic subtropical gyres and cyclonic gyre in the subarctic Pacific, and thus will be largely zonal in the central Pacific where the proposed cruise track will cross this flow.

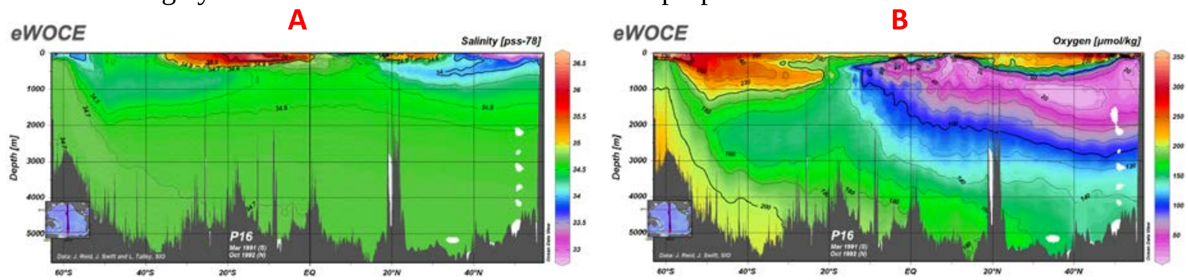
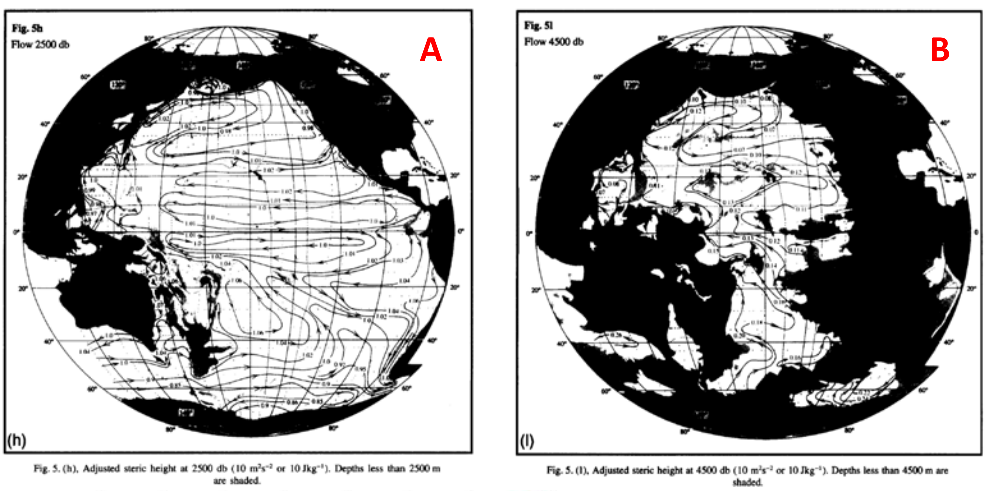


Figure 4. A. Salinity and **B**. Oxygen along the WOCE-CLIVAR P16 Meridional Section.

Deep circulation

NPIW is the densest water (σ_θ = 26.8 kg/m^3) formed in the North Pacific itself. Below this water mass, dense waters are dominated by inflow from the South Pacific, northward across the equator in the west and southward return in the east (Figures 5A and B; Reid, 1997). The densest abyssal water found north of the Pacific Antarctic Rise derives from the circumpolar current, a water mass known as Circumpolar Deep Water (CDW).



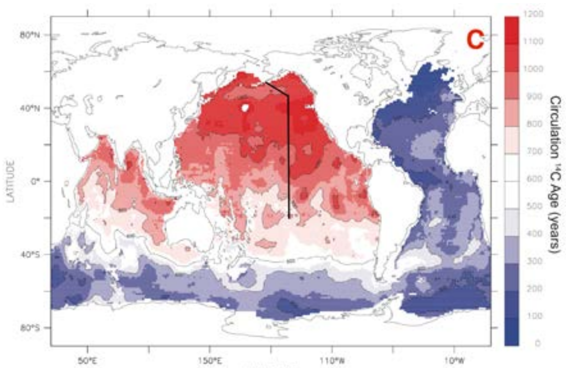


Figure 5. Circulation in the deep waters of the North Pacific Ocean below **A**, 2500 m, and **B**, 4500 m (taken from Reid, 1997), and **C,** map of circulation ^{14}C age below 1500 m (taken from Matsumoto, 2007) with the proposed cruise track overlaid.

The properties of CDW change along the flow path into the North Pacific through vertical diffusion, decreasing the density and allowing return flow in Pacific Deep Water (PDW) between 2000-3000 m. PDW is the farthest extension of North Atlantic-driven thermohaline circulation and shows some of the oldest radiocarbon ages, particularly in the eastern North Pacific (Figure 5C; Matsumoto, 2007), and highest nutrient concentrations in the world ocean. There are few complete sets of TEI data for these oldest waters, the terminus of the global conveyor belt, and the proposed section will provide a unique opportunity to examine the controls on its geochemical properties. Through the deep circulation, O_2 concentrations decrease steadily (Fig. 4B), leading to different conditions for redox-active TEIs. Intersecting the flow of CDW returning as PDW will allow us to examine the fate of TEIs as the water mass ages. We can also define regeneration ratios of nutrients and trace metals, examine scavenging of particle-reactive TEIs, and identify patterns of ligand removal in old, deep waters.

Abyssal circulation, below 4500 m, is topographically-restricted in the basin between the East Pacific Rise (EPR) and the Tonga-Kermadec Ridge in the south and by the Hawaiian Islands and Emperor Sea Mounts in the North (Fig. 5B; Reid, 1997). The size of the basin deeper than 4500 m is small compared to shallower depths. It is also important to note when interpreting TEI distributions that while deep waters generally age into the North Pacific, this flow is not meridional in most cases, but rather follows a circuitous path along the western boundaries, being caught up in the anticyclonic gyre circulation and flowing southward at lower densities in the eastern basin (Figures 5A and B; Reid, 1997).

TEI Biogeochemistry

An examination of TEI biogeochemistry in the Pacific Ocean can be guided by Fig. 2, where distributions, concentrations, speciation, and phase associations (dissolved/particulate) are controlled by inputs across interfaces and internal processes within the water column. While all of these can be examined on a 152° W meridional transect, another important aspect to conducting the cruise along the CLIVAR P16N line is the addition of a time domain to any hydrographic and TEI observations obtained on this transect. The entire P16 line was occupied by the CLIVAR/Repeat Hydrography program in 2006 and 2015, with aerosol (Buck et al., 2013) and dissolved trace element concentrations in the upper 1000m (Milne et al., 2008; Hiscock et al., 2008) obtained on the 2006 CLIVAR cruise. Repeating this line as a GEOTRACES cruise in 2018 will provide full ocean depth (6000m) sampling of the complete GEOTRACES key parameters suite, including the stable, radioactive, and radiogenic isotopes that are critical to interpreting sources and transformations of many TEIs. Anthropogenic TEIs such as Pb and Hg would be expected to show temporal changes (e.g., Noble et al., 2015). However, variations in the distributions of elements with less anthropogenic influence may also yield important information about the sources, sinks, and oceanic residence times. For example, a recent Fe model intercomparison showed that model-estimated residence times of dissolved Fe in the ocean varied by two orders of magnitude, despite the fact that their mean ocean concentrations of iron agreed surprisingly well, revealing large uncertainties in the source and sink terms (Tagliabue, 2016). Having more TEI information in the time domain will be invaluable for assessing the accuracy of these models. There are additional published data sets, although not along 152° W, that can provide additional temporal comparisons (e.g., HOT Station ALOHA, Boyle et al., 2005; JGOFS, Murray et al., 1995; Gordon et al., 1997).

Interfaces

Atmospheric deposition. Global models of mineral aerosol ("dust") deposition from the atmosphere to the ocean's surface (e.g., Jickells et al., 2005) predict an order of magnitude lower fluxes to the Pacific Ocean compared to the Atlantic (Figure 6A). Further, the dust deposition is most elevated in the northern basin since the source of these aerosols is in China's Gobi Desert (Jickells et al., 2005). This predicted flux pattern is borne out by observations along the Repeat Hydrography P16 line along 152° W for Fe deposition (Figure 6B; Buck et al., 2013), as well as for Al and Mn (not shown). Although data for other TEIs are not yet available along the P16 line, measurements in the western portion of the subarctic Pacific's HNLC region (170° E), document inputs of elements such as Se and Ag from Asian fossil fuel combustion (Ranville et al., 2010). Thus, strong flux gradients in atmospherically-derived TEIs are expected along 152°W. These gradients allow questions about the role of atmospheric deposition on TEI

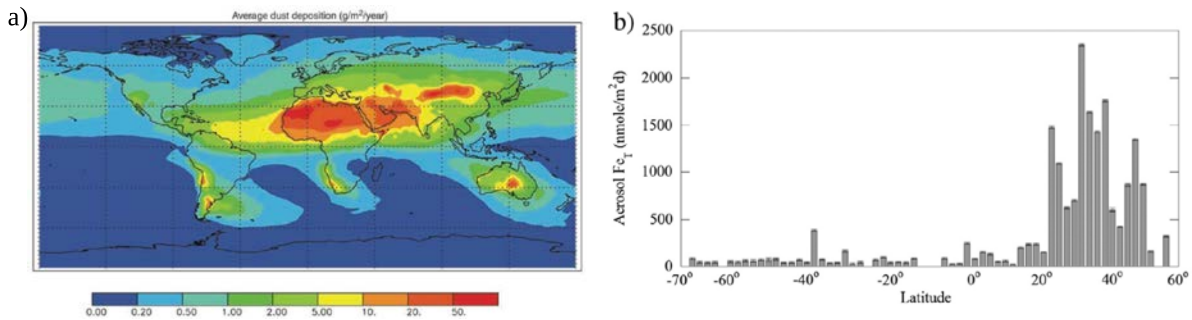


Figure 6. **A**. Model-predicted distribution of dust deposition (Jickells et al., 2005). **B.** Calculated Fe deposition to the Pacific Ocean from aerosol concentrations along the P16 transect (Buck et al., 2013).

cycling to be addressed using direct collection of aerosol TEI samples (e.g., Buck et al., 2013) as well as multiple, water column tracers of dust deposition (e.g., Kadko et al., 2015; Anderson et al. 2016).

Margin sources/sinks. This transect offers the opportunity to study the Aleutian margin input into the Subarctic Pacific. Most of what we know about the sources of TEIs to the Gulf of Alaska is from cruises staged from the British Columbia (BC) coast (e.g., Johnson, 2005) or from south central Alaska (e.g., Lippiatt et al. 2010; Wu and Aguilar-Islas, 2009). These studies have shown that iron can be transported westward from the eastern BC margin from tidal mixing (Cullen et al.,, 2009), and from the eastern and northern margins by mesoscale coastal eddies (Johnson et al., 2005; Lippiatt et al., 2011). However, none of these transport mechanisms are particularly efficient, which explains why Ocean Station Papa (X in center of Figure 7) is typically iron-limited (Maldonado et al., 1999). An advective source of iron from Aleutian Islands was suggested by a general circulation model seeded with a passive tracer at the margin (Fig. 7; Lam et al., 2006), which would be expected to transport margin derived iron and other TEIs into the interior Gulf of Alaska. To our knowledge, this advective source has never been observationally verified. The northern terminus of our transect is designed to sample this putative source across the shelf-slope break at higher resolution than the rest of the transect, and to provide the end-member shelf TEI composition. Significantly, adding shelf stations to GEOTRACES transects was a specific recommendation from a recent GEOTRACES synthesis workshop on boundary exchanges (Charette et al., 2016), and allows the estimation of shelf fluxes of TEIs using a proposed "radium-228 flux gauge" (Charette et al., 2016; Kwon et al., 2014).

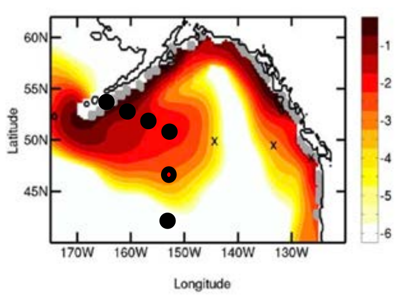


Figure 7. Horizontal distribution of iron-like tracer concentrations in the northeast subarctic Pacific from an ocean general circulation model at the base of the model mixed layer (40 m). Color bar shows the log10 of tracer concentrations in nM, assuming a 1 µmol/m^2-d source flux (Lam et al. 2006). X's are Ocean Station Papa and another station along Line P. Black dots are planned stations for this proposed transect.

In comparison to the other ocean basins, a unique feature of the Pacific is the abundance of volcanic strata surrounding the basin (the "ring of fire"), and inputs of TEIs from the dissolution of these phases is likely to be quite different than those from felsic rocks dominating the Atlantic. In this respect, Nd isotopes may be the best tracer, as documented by more positive/radiogenic εNd values of -2.5 to -3 in mid-water column of the western subarctic Pacific (Amakawa et al., 2004) compared to elsewhere in the basin (Piepgras and Jacobsen, 1988; Amakawa et al., 2009). With the proposed cruise track, sampling of all relevant water masses (see above and Proposed Research), and measurements of the large suite of TEIs including Nd, we expect to be able to discern the importance of this source.

Hydrothermal inputs. Hydrothermal vents are becoming an increasingly recognized input to the ocean of Fe, Mn, and Hg, as well as a sink for particle-reactive trace elements such as Th, Pa, and Pb. Results from GEOTRACES cruises to date have shown that iron-rich hydrothermal plumes are widespread above mid-ocean ridges and are changing the way we think about the fluxes of TEIs from this interface (German et al., 2016; Fig. 1). On the US GEOTRACES Eastern Pacific Zonal Transect (GP16), for example, elevated levels of Fe, Mn, and to a lesser extent Al, were observed in the hydrothermal plume over 4000 km from the ridge axis (Resing et al., 2015). In this plume, marked by elevated levels of ^{3}He (Lupton and Craig, 1981), dissolved and particulate Fe generally correlated with $\delta^{3}He$. The unexpectedly high levels of Fe extending away from the main ridge axis means that this Fe may persist long enough to contribute Fe to Fe-limited surface waters in HNLC regions in the southern ocean (Resing et al., 2015; Tagliabue et al., 2010) and other Pacific HNLC regions (Schlitzer, 2016; Tagliabue et al., 2014). However, plume chemistry can be quite different for each vent system (e.g., Saito et al., 2013; Resing et al., 2015), a point highlighted in the newest review from a 2015 GEOTRACES workshop by German et al. (2016) of hydrothermal vents' roles in global TEI cycling. This variability suggests that extrapolations using TEI/^{3}He ratios must be used with caution; clearly more TEI data from near- and far-field vent plumes are needed, and in fact the proposed cruise will be able to sample at least 3-4 far-field plumes (Figure 8).

The ^{3}He distribution in the Pacific has been measured in previous cruises along line P16 (Figure 8; courtesy of W. Jenkins). These results indicate that the ^{3}He signal observed in the central Pacific has multiple origins, both north and south of the equator, and with non-buoyant plumes settling at different density layers. The highest ^{3}He signals correspond to plumes emanating from the East Pacific Rise (EPR) at 15°S and 9°N, captured in westward flowing zonal currents at 2500 m (Fig. 8). Further north, distinct ^{3}He plumes at 20°N (1100 m) originate at the Loihi Seamount from the west and at 35° N (2000 m) from the Juan de Fuca Ridge (JdFR) to the east, respectively (Lupton, 1998). Particularly exciting for this section is that we will be able to compare the TEI/$\delta^{3}He$ ratios of the distal plumes for the contrasting EPR 9°N and JdFR plumes, both of which have had intensive on-axis process studies, including vent fluid chemistry, via the NSF Ridge 2000 program (Fornari et al., 2012; Kelley et al. 2012).

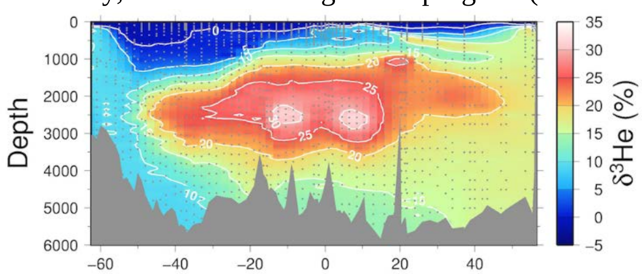


Figure 8. Depth distributions of $\delta^{3}He$ along the P16 line (figure courtesy of W. Jenkins from data produced at WHOI, LDEO and PMEL).

These sources may carry distinct TEI signals and derive from distinctly different background biogeochemical conditions in the water column and at the vent sites. Furthermore, the ambient seawater conditions into which the hydrothermal fluids are dispersed may also play a role in stabilization of the hydrothermal TEI's (e.g., Field and Sherrell, 2000). For example, the rates of Fe oxidation are expected to decrease along the thermohaline flow path as O_2 concentrations and pH decrease as waters age and remineralization products accumulate. Therefore, the proposed sampling will help address some important questions by characterizing the TEI/$\delta^{3}He$ ratios in far-field hydrothermal plumes.

Oxygen Minimum Zones. The proposed section crosses distal portions of the large oxygen minimum zones (OMZs) originating in the eastern tropical Pacific (Figure 9A and B) where geochemical signals of OMZ biogeochemistry are produced. OMZs reflect both interfaces and sites for internal transformations. For example, N* (= $[NO_3^-] + 16 \times [PO_4^{3-}] + 2.9$ µmol/kg) values are lowered in the OMZ, indicative of denitrification removing nitrate, NO_3^- (Gruber and Sarmiento, 1997). Low N* signals clearly extend across the Pacific on $\sigma_\theta = 26.5$ kg/m^3 (Fig. 9B; Deutsch et al., 2001). In fact, N* is thought to behave largely conservatively outside of OMZs (Gruber and Sarmiento, 1997), providing a tracer for OMZ influence on other properties. Recent results from the US GEOTRACES GP16 transect show that elevated $^{15}N/^{14}N$ ratios in NO_3^- also extend as far as 150° W (Peters and Casciotti, unpubl. data). The

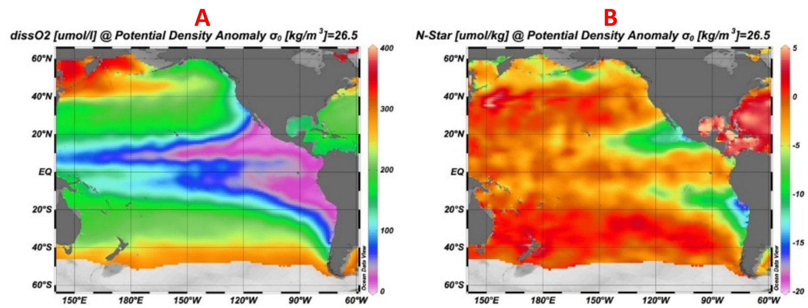


Figure 9. **A**. Distribution of dissolved oxygen on the 26.5 kg/m^3 density surface that is the core of the OMZ originating in the eastern Pacific. **B**. N* distribution along the 26.5 kg/m^3 density surface.

elevated $\delta^{15}N$ signal produced in OMZs is thought to contribute significantly to regional (Cline and Kaplan, 1975; Sigman et al., 2003; Casciotti et al., 2013) and the mean $\delta^{15}N$ signal of deep ocean nitrate (Brandes and Devol, 2002; Sigman et al., 2009). However, how the signals generated in the OMZ are propagated to the broader ocean basin are not well understood. The proposed transect will thus provide critical background information on N isotope signals before and after OMZ influence.

Similar questions could be raised for other redox-sensitive TEIs. Concentrations of trace elements such as Fe, Co, and Mn are elevated in OMZ waters (e.g., Moffett et al, 2007; Noble et al., 2012), most likely due to reductive dissolution (Conway and John, 2014), while other TEIs are scavenged in eastern boundary upwelling regions and grow back in after leaving these regions. Dissolved Fe(II) correlates with nitrite concentration in OMZs (Moffett et al., 2007), and like nitrite, elevated levels of Fe do not extend much beyond the OMZ boundaries, being rapidly consumed upon reintroduction of O_2. By examining the distribution of TEIs such as $\delta^{15}N$-nitrate, Fe, $^{230}Th/^{231}Pa$ in concert, we can begin to identify conservative vs. non-conservative behavior of TEIs outside of low oxygen regions. The space and time scales for attenuation of OMZ-derived signals allow us to can gain a better understanding of the role of oxidation, regeneration, and particle scavenging on TEI signals generated in eastern boundary margins.

Internal cycling

Uptake. As depicted in Fig. 2, internal cycling of TEIs includes biotic and abiotic (scavenging) uptake, export of the resultant particulate TEIs, and regeneration within the water column. In terms of biotic uptake, this transect will give an excellent view of different biomes and the limitations on biological productivity and uptake of TEIs. It will cross from the HNLC conditions in the eastern subarctic Pacific, through the oligotrophic North Pacific subtropical gyre, across the HNLC conditions at the equator, and into the extreme oligotrophic waters of the South Pacific subtropical gyre. Given that the residence times of most TEIs average out short-term variability in processes like primary production, contrasting these different regimes in a single ocean basin is particularly powerful because we can study the hydrographic connection between each of these regions and how processes in one region can impact the supply and bioavailability of TEI's in another. Characterizing the delivery and uptake of nutrient-like TEIs is an important goal for understanding limitation and co-limitation of primary production in HNLC and oligotrophic regimes. For example, there are clear taxonomic and regional variations in the P-normalized cellular quotas of bioactive trace elements (Twining and Baines, 2013) that reflect differences in biochemical demands and environmental availability, and samples from our transect can provide further constraints on this. In a related manner, the chemical speciation of TEIs, particularly for elements like Fe and Cu, strongly affects their uptake by phytoplankton and in turn the TEI effects on abundance of different phytoplankton species (Sunda, 2012). Iron organic ligands have been examined in the coastal (e.g., Hutchins et al., 1998), subarctic (Maldonado and Price, 1999), and equatorial Pacific (e.g., Rue and Bruland, 1997), so a meridional transect will (re)sample all of these regimes and test the global views of iron cycling (e.g., Gledhill and Buck, 2012). Similar studies on copper complexation have been done in these same regimes (e.g., Moffett and Dupont, 2007; Buck et al., 2012).

Scavenging is the abiotic adsorption/desorption of TEIs to marine particles and therefore this mode of uptake occurs throughout the water column, unlike biotic uptake that is concentrated in the euphotic zone; this transect is ideal for testing hypotheses regarding TEI removal by scavenging. Indeed, particle concentrations display tremendous concentration ranges along the planned track (Figure 10; McDonnell, unpubl.), particularly between the subarctic and subtropical gyres. Thus, the range of particle concentrations and measuring the suite of TEIs like Fe and ^{230}Th will allow processes such as scavenging intensity to be constrained. As an example, a recent study of boundary scavenging using ^{230}Th and ^{231}Pa concluded that productivity gradients within a biogeographic province did not lead to changes in scavenging as expected; only productivity gradients across biogeographic provinces did (Hayes et al. 2013). This implies that particle concentration is not a sufficient control on scavenging, and that key drivers for scavenging must be changing across biogeochemical provinces. These factors may include the physical and chemical speciation of dissolved TEIs, and the size distribution and chemical composition of particles, all of which are expected to vary greatly over this transect. Scavenging has also been documented in hydrothermal plumes (Hayes et al., 2015), although hydrothermal particles are a mixture of biotic (including bacterial cells) and abiotic/mineral matrices, so one cannot simply ascribe apparent hydrothermal scavenging to a strictly abiotic processes (Toner et al., 2009). Characterization of potentially important parameters like particle composition and the speciation of dissolved and particulate TEIs, together with scavenging extent across biogeochemical provinces, will undoubtedly help us improve our understanding of this important removal term.

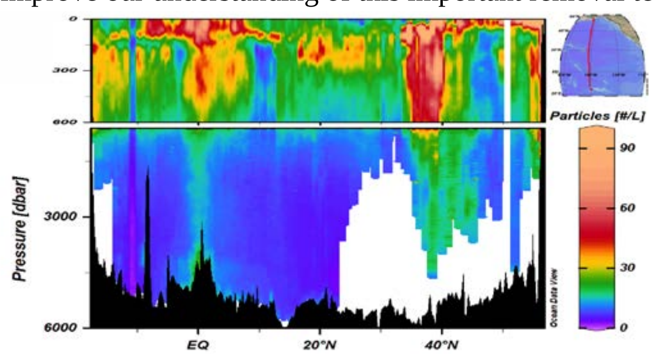


Figure 10. Transect of total particle concentration (#/L) for particles with an equivalent spherical diameter between 100µm and 2.5 cm as determined by the Underwater Vision Profiler (UVP) along the 2015 P16N cruise through the Pacific Ocean from Tahiti to the Gulf of Alaska shelf. Note the scale break at 600m between the upper and lower panels. (Data kindly provided by A. McDonnell).

Export and Regeneration. Export processes involve many biotic (e.g., grazing and defecation) and abiotic (e.g., aggregation) processes, but most of these can be well quantified using TEI/^{234}Th ratios in particles and computed ^{234}Th fluxes (e.g., Owens et al., 2015). In contrast, the return of particulate TEIs to the dissolved state through desorption, particle dissolution, and biotic respiration has received less attention. Indeed, the length scales of regeneration vary by TEI (Twining et al., 2014), but it's not clear how these vary geographically. Plots of TEIs versus AOU may delineate regeneration via respiration (e.g., Redfield stoichiometric ratio) and reversible scavenging processes (e.g., no relation to AOU). On this topic, the sampling of Pacific Deep Water with varying ^{14}C ages, including the oldest, and analyses of the suite of GEOTRACES TEIs, will go a long way towards constraining the rates of regeneration for at least the nutrient-like TEIs with minimal scavenging. The addition of isotope constraints may also help separate regeneration from scavenging (e.g., John and Conway, 2014). Recent synthesis activities have identified important parameters to understand the internal cycling of TEIs, including measurements of physical (colloidal partitioning; e.g., Fitzsimmons et al., 2015) and chemical (e.g., Buck et al., 2015) speciation of dissolved TEIs, particle concentration and composition (e.g., Lam et al., 2015), and single biotic particle analyses (e.g., Twining and Baines, 2013). All of these measurements have been components of most US GEOTRACES cruises to date.

Lessons learned on prior US GEOTRACES cruises

Having very successfully completed three US GEOTRACES sections to date, there are several factors that need to be considered from the "lessons learned" on these cruises. The first lesson is that the complete sampling systems are not just the conventional and trace element-clean rosettes for depth profiles, but also the high resolution surface sampling "fish" that provides 1-2m depth filtered and unfiltered, trace element-clean water to all PIs. Since the trace element-clean GEOTRACES Sampling System cannot acquire water less than 20m deep (Cutter and Bruland, 2012), the fish is essential to completing the profiles for all PIs measuring contamination-prone TEIs. Moreover, it provides large volumes of water continuously for operations such as pre-cleaning filter capsules and trace-metal clean rinsing of aerosol and suspended particles. The second of the additional sampling systems are the McLane in situ pumps that provide high volume particle samples on different filter media (e.g., 51 µm polyester prefilters, 1 µm quartz fiber filters, and 0.8 µm polysulfone filter membranes) and adsorption cartridges for low activity radionuclides. These media have been distributed to over a dozen PI groups measuring particulate trace elements, major particle composition (POC, PIC, opal), short- and long-lived radioactive isotopes (e.g., ^{234}Th, ^{230}Th, ^{228}Ra, ^{210}Pb, ^{210}Po, ^{239}Pu, and more), radiogenic isotopes (Nd and Pb isotopes), and stable isotopes ($\delta^{15}N$, $\delta^{30}Si$, $\delta^{56}Fe$) in all three section cruises to date. In the past, both the fish and in situ pumps have been funded on individual PI proposals, but since so many PIs depend on these sampling systems, they are included in the management proposal to ensure their availability. In the EPZT and Arctic cruises, the costs of HPLC pigment analysis has been shared by the PIs, incurring significant overhead in time and cost for the billing process. Since this is an important ancillary parameter that aids in the interpretation of biological uptake, we have moved pigments into the management proposal. The final lesson learned is that the request for samples vastly exceeds the number of berths available on any UNOLS ship, and therefore the two "Super Techs" for each sampling system has worked very well in getting everyone's samples with excellent quality control and in a cost-effective manner. Historically, the Super Techs sampling the conventional rosette are completely overwhelmed since this is the most used system, and we have budgeted time for the other Super Techs to assist them.

PROPOSED RESEARCH

Based on the three previous management proposals for 2010-2011, 2013, and 2015 US GEOTRACES transects, this proposal seeks to fund the essential sampling operations and infrastructure for the US GEOTRACES Pacific Meridional Transect (GP15) to accomplish TEI research justified in the preceding Background section. The overall success of the proposed cruise relies on individual science projects that will follow, but the management infrastructure underpins all these proposals to come. Thus, the major objectives of this proposal are: **(1) plan and coordinate a 60 day research cruise in 2018; (2) obtain representative samples for a wide variety of TEIs using a conventional CTD/rosette, GEOTRACES Trace Element Sampling Systems (GO-FLO bottles on contamination-free carousel, towed surface fish), and in situ pumps; (3) acquire "conventional" hydrographic data (CTD, transmissometer, fluorometer, oxygen sensor, etc.) along with discrete samples for salinity, dissolved oxygen, algal pigments, and dissolved nutrients at micro- and nanomolar levels; (4) ensure that proper QA/QC protocols are followed and reported, as well as fulfilling all GEOTRACES intercalibration protocols; (5) prepare and deliver all hydrographic data to the GEOTRACES Data Assembly Centre (via the US BCO-DMO data center); and (6) coordinate all cruise communications between investigators, including preparation of a hydrographic report/publication.** These objectives mirror those in the preceding US GEOTRACES transects which have resulted in high quality data (e.g., many of those in Fig. 1) for use by the marine biogeochemistry and modeling communities, and rapid advances in our understanding of TEIs in the ocean system (see publications list on the International GEOTRACES web site). The following sections detail how we will accomplish these objectives.

Cruise track and timing

From the biogeochemical and physical oceanography reviews in the Background section, planning at the 2008 Pacific Implementation Workshop (Moffett and German, 2009), and recent synthesis workshops, key features that should be sampled on the meridional cruise include: cross margin/island arc fluxes at the northern extreme; hydrothermal plumes emanating from the JdFR and EPR; subarctic HNLC and ultra-oligotrophic surface waters; equatorial upwelling regimes and subsurface counter- and under-currents; intermediate waters; OMZ waters; and the old, deep Pacific waters. With a planned 60 day cruise length, our well-established station times (next section) allow a total of 41 stations (types defined below) to be occupied on the transect shown in Figure 11: test/rinse station, 18 Full (including those on the diagonal margin portion), 5 Super, and 17 Demi. We have assumed the departure port of Dutch Harbor, Alaska since this would allow high resolution sampling of this margin, including deep waters of the Aleutian Trench. From there, sampling proceeds along a diagonal section to meet the Repeat Hydrography P16 line along 152° W in the center of the HNLC waters of the subarctic Pacific (Fig. 11). Conducting the cruise from North to South minimizes transit time since most of the cruise would have the Trade Winds on our aft quarter, and a July or August 2018 start would best fit fair weather windows in both hemispheres.

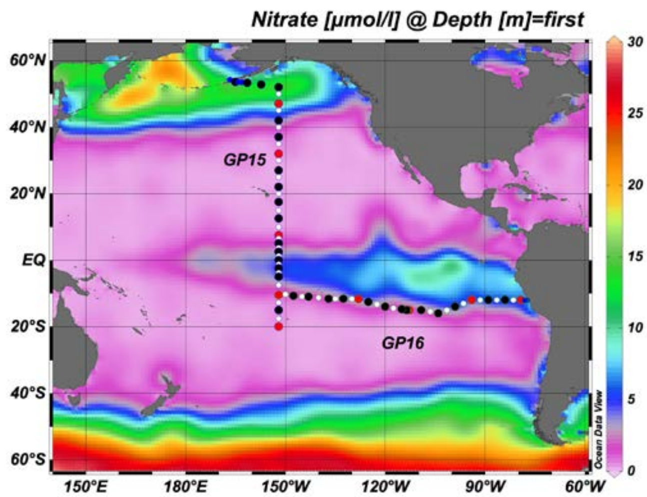


Figure 11. Proposed cruise track for the 2018 Meridional Pacific Transect (GP15) overlaid on annual average, surface nitrate concentrations from the World Ocean Atlas 2013. Large black and red symbols indicate Full and Super stations, respectively, while small blue and white symbols show Slope and Demi stations, respectively. Stations from the 2013 Eastern Pacific Zonal Transect (GP16) are shown using the same symbol scheme.

From north to south, Super stations are located to: crossover/intercalibrate with the 2017 Japanese GP02 line at 47°N (H. Obata, pers. comm.), the nominal Juan de Fuca plume at 32°N (Fig. 8), northern EPR plume at 7.5°N (Fig. 8), the equator, and the ultra-oligotrophic South Pacific Central Gyre at the terminus of the transect. Based on the GEOTRACES convention that minimum spacing for full-depth water column stations is 5° latitude, the remaining stations are Full at this spacing, although they are at higher 2.5° resolution about the equatorial upwelling region. Shallow 1000 m Demi stations are placed between each Full or Super station to increase sampling resolution in the upper water column. It is very important to note that the exact location of all stations except the Crossover and terminal stations will be agreed upon at the pre-cruise PI meeting 6-9 months prior to the cruise (see Management section below).

Sampling methodology

Along the cruise track shown in Fig. 11, three types of stations will be occupied. Full stations will involve sampling the water column using three casts each of the GEOTRACES and conventional rosette sampling systems. We overlap two depths (bottom of first, with top of second, etc.) to allow intercalibration via shared samples (e.g., different labs can sample the same depths), giving a vertical coverage of 34 depths per station. The conventional rosette is used to collect additional samples for all parameters depending on what projects are funded. McLane in situ pumps sample 16 of these depths with 2 hydrocasts, using 8 pumps per cast. Based on experience on the 2013 EPZT cruise, a Full station takes 36 hours to complete. A Super station that includes 6 additional conventional CTD rosette casts, and one additional pump cast, takes 60 hours to complete. Demi stations sample the upper 1000 m using only one cast each of the GEOTRACES and conventional rosettes, taking a total of 2 hours to complete. For all stations, sampled depths are not fixed, but are targeted in response to the observed hydrography, desired sampling features (e.g., chlorophyll and particle maxima, hydrothermal plume, equatorial undercurrents, nepheloid layer), and in the equatorial region, use of the ADCP current profiles to identify the various under- and counter-currents (e.g., Fig. 3). This routine for selecting sample depths has worked excellently on the North Atlantic, Eastern Pacific, and Arctic cruises.

The water sampling systems and protocols used on all previous US GEOTRACES cruises will be used on this proposed GP15 section. The overall procedures for conducting this cruise are documented in the Sampling and Sample-Handling Protocols for GEOTRACES Cruises “cookbook” (Cutter et al., 2014), so they will not be described here. The GEOTRACES cookbook includes methods for all the sampling done under this management proposal: trace element-clean for dissolved and particulate (membrane-filtered) samples, surface towed fish samples, conventional CTD/rosette sampling, and in situ, high volume particle samples. In addition, the US GEOTRACES clean sampling system will be used and its performance has been thoroughly tested and described (Cutter and Bruland, 2012). For TEIs that are not contamination-prone and to sample water column hydrography, we again will use the 12-position, 30L bottle CTD/rosette operated by the Scripps Institution of Oceanography’s Oceanographic Data Facility (SIO/ODF). High-quality hydrographic data obtained from this system are crucial for characterizing water masses as well as for testing the performance of GO-FLO bottles (see Cutter and Bruland, 2012; Cutter and Measures, 1999). In this respect, shipboard measurements of micromolar inorganic nutrients (nitrate, silicate, and phosphate), salinity and dissolved oxygen will be made by SIO/ODF to GO-SHIP standards (see below), while nanomolar nutrients in oligotrophic waters are determined by Cutter’s lab.

As noted in the Lessons Learned section above, we have included large volume particle sampling and towed surface fish sample acquisition in this management proposal. Particulate sample and McLane pump handling will follow the appropriate methods described in the GEOTRACES Cruise Protocols (Cutter et al., 2014) and used during the US NAZT, EPZT, and Arctic cruises (Lam et al., 2015; Ohnemus and Lam, 2015). For near-surface sampling for dissolved TEIs we will use a trace metal-clean “fish” (e.g., De Jong et al., 1998; Vink et al., 2000; Cutter et al., 2014) that is deployed ca. 8-10 m from the ship’s quarter using an Al boom, and to which is attached Teflon-lined tubing that leads to a deck-mounted Teflon diaphragm pump. This system provides flow rates of up to 5L/min into the clean lab van while steaming at 10+ knots and the water is capsule filtered or taken unfiltered. This system will be provided by the Management Team, but available to all PIs who wish to sample these near surface waters.

Analytical Methods

Hydrography and nutrients. Accurate hydrography and nutrient data are essential for elucidating biogeochemical processes and physical transport and mixing that can affect TEI distributions. To insure the best hydrography possible, the SIO/ODF team overseen by Jim Swift will perform measurements fully compliant with GO-SHIP/Repeat Hydrography protocols, including determinations of salinity, dissolved oxygen, phosphate, nitrate, nitrite, and silicate on discrete samples from the ODF, GEOTRACES, and Fish sampling systems; details are in the subcontract to Casciotti/Stanford (Stanford Budget). In addition to ODF’s nutrient data, Cutter’s lab will determine nitrite, nitrate, and phosphate at nanomolar concentrations for all samples in the upper 200 m when below the ODF detection limits. For this, a continuous-flow Astoria Pacific Rapid Flow Analyzer is equipped with long path length (2.2 m), liquid core waveguide cells as fully described by Zhang (2000) for nitrite and nitrate, and by Zimmer and Cutter (2012) for phosphate.

Zn contamination. Samples from the GEOTRACES sampling system GO-FLO bottles will be analyzed onboard for dissolved Zn as it is an excellent indicator of potential sampling contamination (Cutter and Bruland, 2012). For these analyses we will employ the well-tested flow injection-fluorometric detection system originally described by Nowicki et al. (1994) and later modified by Gosnell et al. (2012) and Wyatt et al., (2014). These measurements will be made at all of the stations and all GO-FLOs in the first week of the cruise, and subsequently if GO-FLOs are changed or repaired.

Pigments. Samples will be collected for pigment analysis from the upper 6 samples (~200 m) of each Full and Super station. Water collected from the ODF rosette will be sampled into dark 2L polyethylene bottles and gently filtered through 25 mm GF/F filters. Samples will be frozen at -80°C and shipped to Oregon State University for HPLC pigment determinations.

Management team responsibilities/roles

Overall. The management team is the three PIs on this proposal who will oversee implementation of the US GEOTRACES Pacific Meridional Transect (GP15), including all aspects of logistics, interaction with the ship operator and agents, communication with the science community, and data management (see Data Management Plan in Supplementary Documents). Prior to the cruise, we will follow the procedure used for the previous US cruises and host a Meridional Cruise workshop 5-7 October 2016 where interested PIs can learn about the background science, rationale, and logistics of the cruise, present their statements of interest, and set up potential collaborations well before their proposal deadline; funding for this workshop comes from the US GEOTRACES Project Office. In addition, statements of interest from individual PIs will be posted on the US GEOTRACES web site to facilitate coordination of logistics and creation of scientific collaborations. Participation on this cruise will be open to any US PI who proposes high quality research that supports the GEOTRACES goals; as of 11 August 2016, 63 PIs from 36 separate institutions have expressed interest in attending this workshop, an excellent reflection of the interest in the cruise from a broad spectrum of the chemical oceanography community. After funding decisions on individual science proposals, we will coordinate a PI pre-cruise meeting in early 2018 to determine ship-board requirements and operations including the number, type and exact locations of the stations to be occupied along the section. At sea, we will provide for all sample acquisition, quality control and archiving of the appropriate operational metadata (navigation, event logs, etc.) and hydrographic data following previously-established GEOTRACES and GO-SHIP protocols. SIO/ODF will be in charge of hydrographic and nutrient data acquisition and will work with the management team on shipboard data management (see Data Management Plan in Supplemental Documents and SIO/ODF subcontract in Stanford Budget). Water and large-volume particle sampling will use the facilities described above. We anticipate that individual PI(s) will provide the aerosol and precipitation sampling equipment, as on the 3 previous cruises. The management team will coordinate all on-board water sampling, ensure smooth and efficient operation of all station-related activities and be responsible for acquisition of all essential hydrographic data (CTD, salinity, nutrients, oxygen, and pigments). Working with ODF, the management team will also be responsible for establishing and monitoring both GO-FLO and Niskin integrity using shipboard hydrographic measurements, as well as dissolved Zn determinations. The management team will be responsible for the quality control and archiving of all ship-board measurement data and for making all data and meta-data available to on-board participants. Post cruise, the management team will be responsible for ensuring the timely transmission of all data and meta-data acquired during the cruise to the US GEOTRACES data archive (BCO-DMO, WHOI) who, in turn, will be responsible for transferring all such data and metadata to the International GEOTRACES Data Assembly Centre (GDAC; see Data Management Plan). With respect to data management and intercalibration, Cutter started the international GEOTRACES Intercalibration program in 2005 and co-chaired the S&I committee until 2016, while Casciotti is a current member of the S&IC. The management team will also be responsible, together with Jim Swift (SIO/ODF), for creating a final cruise report and a “hydrographic synthesis” of publishable quality, describing the basic context (water mass structure, major current flows, etc.) that will aid the interpretation of all TEI data (e.g., Jenkins et al., 2015; Peters et al., in prep.). Finally, the management team will host a post-cruise synthesis meeting (US GEOTRACES Project Office funded) ca. 1.5 years after the cruise to promote collaboration, discussion, and manuscript preparation among the participants.

Specific Responsibilities. **Cutter** will act as chief scientist on the cruise and lead investigator of the management team. He has participated as a Co-PI on virtually every US GEOTRACES cruise and was co-chief scientist on the 2011 NAZT with Ed Boyle. He runs the US GEOTRACES Sampling Facility and therefore will coordinate all trace element sampling and sample handling activities on the cruise (clean lab, winch/CTD-Carousel, GO-FLO sampling systems). He will supervise his senior Laboratory Supervisor Lisa Oswald who will be in charge of the cruise logging (e.g., Event Log) in collaboration with the ODF Data Manager as she did in the 2015 Arctic cruise. She will also measure Zn concentrations from GO-FLO samples in the first part of the cruise and nanomolar nutrients later in oligotrophic waters. Cutter will supervise the two "Super-Techs" to be contracted for all trace element sampling from the GEOTRACES system at sea. Finally, Cutter will be the primary point of contact with the ship schedulers and oversee acquisition of any required international sampling clearances (e.g., French Polynesia). **Lam** will sail as co-leader on the expedition, with primary responsibility for coordinating McLane pump sampling activities, including supervising the two Super-Techs for the pump operations. She will also oversee the Broader Impacts/outreach activities during the cruise. **Casciotti** will sail as co-leader of the expedition, and will be the primary interface with the ODF group, subcontracted by Stanford, for acquisition of hydrographic data; she also will take care of the pigments determinations (see details in Stanford Budget). Two "Super-Techs" who will be contracted to oversee TEI sampling and sample handling at sea for all waters collected from the ODF CTD/rosette will be under her supervision.

Broader Impacts

This meridional cruise will vastly improve our understanding of TEI cycling, including inputs, outputs and internal cycling as depicted in Figure 2. This work will provide TEI data to a broad scientific community through timely data sharing and meeting coordination. This project will also provide baseline measurements of TEIs in the Clarion-Clipperton fracture zone (~7.5°N-17°N, ~155°W-115°W) where large-scale deep sea mining is planned. Large areas of this zone (ca. 1,000,000 km^2) are already under contract for mining exploration of Cu- and Ni-rich Mn nodules (Hein et al., 2013), with large scale mining activities expected to begin in 2025. Deep sea mining activities are expected to lead to significant benthic habitat disturbance resulting from direct mining of the seabed, mining tailings, and fine sediment mobilization (Wedding et al., 2013). Environmental impact assessments are underway in partnership with the mining industry (Lodge et al., 2014), but the effect of mining activities on TEIs in the water column is one that could be uniquely assessed by the GEOTRACES community. GP15 is proposed to go through the western end of this zone in 2018, and provide baseline data before major mining activities commence.

In terms of communicating our science to a larger audience, we will recruit an early career freelance science journalist with interests in marine science and oceanography to participate on the cruise and do public outreach, photography and/or videography, and social media from the ship, as well as to submit articles about the research to national media. We have been in contact with the director of the renowned UCSC Science Communication program, Rob Irion, who has agreed to advise us on the recruitment of a suitable candidate when the time comes (see letter of support). In brief, we plan to advertise the opportunity on science writing job boards for recent graduates of programs such as the UCSC Science Communication program. Graduates of science writing programs such as this typically have at least a bachelor's degree in a scientific field, but importantly have had practical training and experience with news, long-form writing, and multimedia skills. They have had professional journalists and editors as instructors, as well as internships at newspapers and magazines. The specific format of the outreach from our cruise will depend on the person we recruit, but the involvement of a professional science journalist will not only ensure a high quality product, but also give us access to media outlets that research scientists don't typically have and increase the visibility and impact of our work. We will likely entrain the journalist within the McLane pump team so that they can experience all aspects of a research project at sea. In addition to a professional journalist on the cruise, there is a long tradition of student, postdoc, and technician blogs on US GEOTRACES cruises starting with the 2008 Intercalibration cruise, and we fully support these outreach activities in addition to our conventional means of communicating our science on University web sites and talks to local citizen groups like clubs and associations.

The Stanford component will involve a graduate student Super Tech, who will help organize and prepare for the cruise, go to sea to help sample parameters from the ODF rosette, and help with demobilization. This experience will be excellent training for the graduate student, and they will gain networking opportunities through the cruise, as well as pre-cruise planning and post cruise data synthesis meetings. It is expected that this student will remain involved with the GEOTRACES program, possibly through analysis of samples and/or hydrographic data resulting from the project.

Results from Previous Research

K.L. Casciotti. NSF award OCE 09-60605, *Collaborative Research: GEOTRACES Atlantic Section Nitrate Isotope Measurements*. 05/01/10-04/30/14, $237,716 to KLC. **Intellectual Merit**: The major goal of this project was to develop an N-isotope based budget for N_2 fixation in the tropical Atlantic. By combining data from GA03 with those from CoFeMUG and AMT16 in an inverse model we aimed to calculate how much N_2 fixation (introduction of low δ^{15}N-material) is needed to explain the data. The initial description and interpretation is complete (Marconi et al., 2015), but more can be done with the data as we combine it with other nitrate isotope data from the basin, and with other parameters measured in GEOTRACES (Hastings et al., 2013). These results have been presented at the Gordon research conference in Chemical Oceanography and at GEOTRACES Atlantic data workshops. They have been submitted to BCO-DMO, were included in IDP2014, and have been published in the second special issue dedicated to results from this cruise. **Broader impacts**: This grant supported two early career female investigators and the training of two graduate students. In addition, it led to multiple presentations at national meetings, including three student presentations, one invited talk, and more than eight invited seminars. This project also furthered efforts for nitrate isotope intercalibration between Sigman and Casciotti labs. **Products:** Hastings et al., 2013; Marconi et al., 2015.

G.A. Cutter. OCE-0926092, 8/1/2009-7/31/2012, $317,258, Collaborative Research: Management and logistics operations for the U.S. GEOTRACES zonal North Atlantic survey. **Intellectual Merit:** This grant was for the first US GEOTRACES cruises, a zonal transect across the N. Atlantic in 2010 and 2011 (two because Knorr broke down on the 2010 cruise). We were in charge of all contamination-prone sampling operations using the US GEOTRACES Sampling Facility and determinations of nanomolar phosphate and nitrate in samples from the towed fish system and depth profiles in the upper 200 m. **Products:** Cutter hosted the pre-cruise PI meeting in 2010 and post cruise data synthesis workshop in 2013 at ODU, and was the co-chair of a special session on the NAZT at the 2012 Ocean Sciences Meeting. To date, five publications resulted from this grant: Cutter and Bruland, 2012; Zimmer and Cutter, 2012; Cutter, 2013; Boyle et al., 2015; and Jenkins et al., 2015. **Broader Impacts**: Aspects of these GEOTRACES research are incorporated into graduate and undergraduate courses taught by Cutter, and our cruises enabled 9 postdocs, 10 graduate students, and 1 undergraduate student to participate and learn essential trace element sampling and analytical skills.

P. J. Lam: NSF-OCE-0963026, $354K (2010-2013) *"US GEOTRACES North Atlantic Section: Analysis of Key Trace Elements in Size-fractionated Marine Particles*". **Synopsis:** We collected and analyzed the first full ocean depth transect of size-fractionated marine particle composition. **Intellectual Merit:** The input of mineral dust from the Sahara dominated the cycling of major and minor elements in the North Atlantic. **Broader Impacts:** This project was a major part of the Ph.D. thesis of D. Ohnemus (graduation Sept. 2013). Two female undergraduates (J. Ventour; C. DePass) from historically black universities were trained on this project through the Woods Hole Partnership Education Program. **Products:** This has so far resulted in thirteen published manuscripts (Lerner et al., 2016; Hayes *et al.*, 2015; Jeandel *et al.*, 2015; Lam and Marchal, 2015; Lam *et al.*, 2015a; Lam *et al.*, 2015b; Lamborg *et al.*, 2014; Marchal and Lam, 2012; McDonnell *et al.*, 2015; Noble *et al.*, 2015; Ohnemus and Lam, 2015; Revels *et al.*, 2015; Twining *et al.*, 2015) and several manuscripts still in prep.

REFERENCES

Altabet M.A., Francois, R., 1994. Sedimentary nitrogen isotopic ratio as a recorder for surface ocean nitrate utilization. Global Biogeochem. Cycles 8(1), 103–116.

Amakawa, H., Sasaki, K., Ebihara, M., 2009. Nd isotopic composition in the central North Pacific. Geochim. Cosmochim Acta, 73, 4705-4719.

Amakawa, H., Nozaki, Y., Alibo, D.S., Zhange, J. Fukugawa, K. Nagai, H., 2004. Neodymium isotopic variations in Northwest Pacific waters. Geochim. Cosmochim Acta, 68, 715-727.

Anderson, R.F., Bacon, M.P., Brewer, P.G., 1983. Removal of 230Th and 231Pa at ocean margins. Earth and Planetary Science Letters 66 (0), 73-90. 10.1016/0012-821x(83)90127-9.

Anderson, R.F., Cheng, H., Edwards, R.L., Fleisher, M.Q., Hayes, C.T., Huang, K.-F., Kadko, D., Lam, P.J., Landing, W., Lao, Y., Lu, Y., Measures, C.I., Moran, S.B., Morton, P., Ohnemus, D.C., Shelley, R.U., 2016. How well can we quantify dust deposition to the ocean? Phil. Trans. R. Soc. A. In press.

Anderson, R.F., E. Mawji, G.A. Cutter, C.I. Measures, and C. Jeandel. 2014. GEOTRACES - Changing the Way We Explore Ocean Chemistry. Oceanography, special issue - Changing Ocean Chemistry, 27: 50-61.

Boyle, E.A., R.F. Anderson, G.A. Cutter, R. Fine, W.J. Jenkins, and M. Saito. 2015. Introduction to the U.S. GEOTRACES North Atlantic Transect (GA-03): USGT10 and USGT11 cruises. Deep-Sea Res. II, 116: 1-5.

Boyle, E.A., Bergquist, B.A., Kayser, R.A. Mahowald, N., 2005. Iron, manganese, and lead at Hawaii Ocean Time-series station ALOHA: temporal variability and an intermediate water hydrothermal plume. Geochim. Cosmochim. Acta, 69, 933-952.

Brand, L.E., Sunda, W.G., Guillard, R.R.L., 1986. Reduction of marine phytoplankton reproduction rates by copper and cadmium. Journal of Experimental Marine Biology and Ecology 96 (3), 225-250. http://dx.doi.org/10.1016/0022-0981(86)90205-4.

Brandes J.A., Devol A.H. 2002. A global marine fixed nitrogen isotopic budget: Implications for Holocene nitrogen cycling. Global Biogeochem Cycles.16(4):1120.

Bruland, K.W., Franks, R.P., Knauer, G.A., Martin, J.H., 1979. Sampling and analytical methods for the determination of copper, cadmium, zinc, and nickel at the nanogram per liter level in sea water. Analytica Chimica Acta 105, 233-245. http://dx.doi.org/10.1016/S0003-2670(01)83754-5.

Buck, C.S., Landing, W.M., Resing, J., 2013. Pacific Ocean aerosols: Deposition and solubility of iron, aluminum, and other trace elements. Marine Chemistry 157, 117-130.

Buck, K.N., Moffett, J., Barbeau, K.A., Bundy, R.M., Kondo, Y., Wu, J., 2012. The organic complexation of iron and copper: an intercomparison of competitive ligand exchange-adsorptive cathodic stripping voltammetry (CLE-ACSV) techniques. Limnology and Oceanography: Methods 10 (7), 496-515. 10.4319/lom.2012.10.496.

Buck, K.N., Sohst, B., Sedwick, P.N., 2015. The organic complexation of dissolved iron along the U.S. GEOTRACES (GA03) North Atlantic Section. Deep Sea Res. II, 116: 152-165. http://dx.doi.org/10.1016/j.dsr2.2014.11.016.

Casciotti KL, Buchwald C, McIlvin M. 2013. Implications of nitrate and nitrite isotopic measurements for the mechanisms of nitrogen cycling in the Peru oxygen deficient zone. Deep Sea Res I, 80:78–93.

Charette, M.A., Lam, P.J., Lohan, M.C., Kwon, E.Y., Hatje, V., Jeandel, C., Shiller, A.M., Cutter, G.A., Thomas, A., Boyd, P.W., Homoky, W.B., Milne, A., Thomas, H., Andersson, P.S., Porcelli, D., Tanaka, T., Geibert, W., Dehairs, F., and Garcia-Orellana, J. 2016. Coastal ocean and shelf-sea biogeochemical cycling of trace elements and isotopes: lessons learned from GEOTRACES. Phil. Trans. R. Soc. A. In press.

Cline JD, Kaplan IR. 1975. Isotopic fractionation of dissolved nitrate during denitrification in the Eastern Tropical North Pacific Ocean. Mar Chem., 3, 271–99.

Conway, T.M., John, S.G., 2014. Quantification of dissolved iron sources to the North Atlantic Ocean. Nature 511 (7508), 212-215. 10.1038/nature13482

Cullen, J.T., Chong, M., Ianson, D., 2009. British Columbian continental shelf as a source of dissolved iron to the subarctic northeast Pacific Ocean. Global Biogeochem. Cycles 23.
Cutter, G.A. 2013. Intercalibration in chemical oceanography – getting the right number. Limnol. Oceanogr. Methods, 11: 418-424.
Cutter, G.A., Bruland, K.W. 2012. Rapid and non-contaminating sampling system for trace elements in global ocean surveys. Limnol. Oceanogr. Methods, 10, 425-436.
Cutter, G.A., Measures, C.I., 1999. The 1996 IOC contaminant baseline survey in the Atlantic Ocean from 33°S to 10°N: introduction, sampling protocols, and hydrographic data. Deep Sea Research Part II: Topical Studies in Oceanography 46 (5), 867-884. http://dx.doi.org/10.1016/S0967-0645(99)00005-3.
Cutter, G.A., P. Andersson, L. Codispoti, P. Croot, R. Francois, M. Lohan, H. Obata, and M.R. van der Loeff. 2014. Sampling and Sample-handling Protocols for GEOTRACES Cruises, Version 2.0. GEOTRACES web site: http://www.geotraces.org/images/stories/documents/intercalibration/Cookbook.pdf
Deutsch C., Gruber, N., Key, R.M., Sarmiento, J.L., Ganaschaud, A., 2011. Denitrification and N2 fixation in the Pacific Ocean. Global Biogeochem Cycles,15(2), 483–506.
de Jong, J.T.M., den Das, J., Bathmann, U., Stoll, M.H.C., Kattner, G., Nolting, R.F., de Baar, H.J.W., 1998. Dissolved iron at subnanomolar levels in the Southern Ocean as determined by ship-board analysis. Analytica Chimica Acta 377 (2–3), 113-124. http://dx.doi.org/10.1016/S0003-2670(98)00427-9.
Falkowski, P.G., Barber, R.T., Smetacek, V., 1998. Biogeochemical controls and feedbacks on ocean primary production. Science 281 (5374), 200-206.
Favorite, F., Dodimead, A., J. , Nasu, K., 1976. Oceanography of the subarctic Pacific region, 1960–1972. Int. North Pac. Fish. Comm. Bull 33, 1-187.
Field, M.P., Sherrell, R.M., 2000. Dissolved and particulate Fe in a hydrothermal plume at 9°45′N, East Pacific Rise:: Slow Fe (II) oxidation kinetics in Pacific plumes. Geochimica Et Cosmochimica Acta 64 (4), 619-628. 10.1016/s0016-7037(99)00333-6.
Fitzsimmons, J.N., Carrasco, G.G., Wu, J., Roshan, S., Hatta, M., Measures, C.I., Conway, T.M., John, S.G., Boyle, E.A., 2015. Partitioning of dissolved iron and iron isotopes into soluble and colloidal phases along the GA03 GEOTRACES North Atlantic Transect. Deep Sea Research Part II: Topical Studies in Oceanography 116, 130-151. http://dx.doi.org/10.1016/j.dsr2.2014.11.014.
Fornari, D.J., Von Damm, K.L., Bryce, J.G., Cowen, J.P., Ferrini, V., Fundis, A., Lilley, M.D., Luther III, G.W., Mullineaux, L.S., Perfit, M.R., 2012. The East Pacific Rise between 9 N and 10 N: Twenty-five years of integrated, multidisciplinary oceanic spreading center studies. Oceanography, 25(1), 18-43
GEOTRACES, 2006. *Science Plan*. Available online at http://www.geotraces.org/science/science-plan: Scientific Committee on Oceanic Research.
German, C.R., Casciotti, K.L., Dutay, J.-C., Heimbürger, L.-E., Jenkins, W.J., Measures, C.I., Mills, R.A., Obata, H., Schlitzer, R., Tagliabue, A., Turner, D.R., Whitby, H., 2016. Hydrothermal impacts on trace element and isotope ocean biogeochemistry. Philosophical Transactions of the Royal Society A., in press.
Gledhill, M., Buck, K.N., 2012. The Organic Complexation of Iron in the Marine Environment: A Review. Frontiers in Microbiology 3, 69. 10.3389/fmicb.2012.00069.
Gordon, R.M., Coale, K.H., Johnson, K.S., 1997. Iron distributions in the equatorial Pacific: Implications for new production. Limnol. Oceanogr. 42: 419-431.
Gosnell, K.J., Landing, W.M., Milne, A., 2012. Fluorometric detection of total dissolved zinc in the southern Indian Ocean. Marine Chemistry 132–133, 68-76. http://dx.doi.org/10.1016/j.marchem.2012.01.004.
Gruber, N., Sarmiento, J.L., 1997. Global patterns of marine nitrogen fixation and denitrification. Global Biogeochemical Cycles 11 (2), 235-266. 10.1029/97GB00077.

Hastings, M.G., Casciotti, K.L., Elliott, E.M., 2013. Stable isotopes as tracers of anthropogenic nitrogen sources, deposition, and impacts. Elements 9 (5), 339-344.
Hayes, C.T., Anderson, R.F., Fleisher, M.Q., Vivancos, S.M., Lam, P.J., Ohnemus, D.C., Huang, K.-F., Robinson, L.F., Lu, Y., Cheng, H., Edwards, R.L., Moran, S.B., 2015. Intensity of Th and Pa scavenging partitioned by particle chemistry in the North Atlantic Ocean. Marine Chemistry 170 (0), 49-60. http://dx.doi.org/10.1016/j.marchem.2015.01.006.
Hayes, C.T., Anderson, R.F., Jaccard, S.L., François, R., Fleisher, M.Q., Soon, M., Gersonde, R., 2013. A new perspective on boundary scavenging in the North Pacific Ocean. Earth and Planetary Science Letters 369–370 (0), 86-97. http://dx.doi.org/10.1016/j.epsl.2013.03.008.
Hein, J.R., Mizell, K., Koschinsky, A., Conrad, T.A., 2013. Deep-ocean mineral deposits as a source of critical metals for high- and green-technology applications: Comparison with land-based resources. Ore Geology Reviews 51, 1-14. http://dx.doi.org/10.1016/j.oregeorev.2012.12.001.
Hiscock, W., Landing, W., Buck, C., 2008. High-Resolution Dissolved Fe and Al along 150 W in the North Pacific Ocean: Results from the CLIVAR Repeat Hydrography P16N Section. AGU Fall Meeting Abstracts, p. 01.
Hutchins, D.A., DiTullio, G.R., Zhang, Y., Bruland, K.W., 1998. An iron limitation mosaic in the California upwelling regime. Limnology and Oceanography 43 (6), 1037-1054.
Jeandel, C., Rutgers van der Loeff, M., Lam, P.J., Roy-Barman, M., Sherrell, R.M., Kretschmer, S., German, C., Dehairs, F., 2015. What did we learn about ocean particle dynamics in the GEOSECS–JGOFS era? Progress in Oceanography 133, 6-16. http://dx.doi.org/10.1016/j.pocean.2014.12.018.
Jenkins, W.J., W.M. Smethie, Jr., E.A. Boyle, and G.A. Cutter. 2015. Water mass analysis for the U.S. GEOTRACES North Atlantic Sections. Deep-Sea Res. II, 116: 6-20.
Jickells, T.D., An, Z.S., Andersen, K.K., Baker, A.R., Bergametti, G., Brooks, N., Cao, J.J., Boyd, P.W., Duce, R.A., Hunter, K.A., Kawahata, H., Kubilay, N., laRoche, J., Liss, P.S., Mahowald, N., Prospero, J.M., Ridgwell, A.J., Tegen, I., Torres, R., 2005. Global iron connections between desert dust, ocean biogeochemistry, and climate. Science 308 (5718), 67-71.
John, S.G., Conway, T.M., 2014. A role for scavenging in the marine biogeochemical cycling of zinc and zinc isotopes. Earth and Planetary Science Letters 394 (0), 159-167. http://dx.doi.org/10.1016/j.epsl.2014.02.053.
Johnson, W.K., Miller, L.A., Sutherland, N.E., Wong, C.S., 2005. Iron transport by mesoscale Haida eddies in the Gulf of Alaska. Deep-Sea Research Part Ii-Topical Studies in Oceanography 52 (7-8), 933-953.
Juranek, L.W., Quay, P.D., Feely, R.A., Lockwood, D., Karl, D.M., Church, M.J., 2012. Biological production in the NE Pacific and its influence on air-sea CO2 flux: Evidence from dissolved oxygen isotopes and O2/Ar. J. Geophys. Res. 117 (C5), C05022. 10.1029/2011jc007450.
Kadko, D., Landing, W.M., Shelley, R.U. 2015. A novel tracer technique to quantify the atmospheric flux of trace elements to remove ocean regions. J. Geophys. Res. Ocean, 120, 848-858.
Karl, D., Letelier, R., Tupas, L., Dore, J., Christian, J., Hebel, D., 1997. The role of nitrogen fixation in biogeochemical cycling in the subtropical North Pacific Ocean. Nature 388 (6642), 533-538.
Kaupp, L.J., Measures, C.I., Selph, K.E., Mackenzie, F.T., 2011. The distribution of dissolved Fe and Al in the upper waters of the Eastern Equatorial Pacific. Deep Sea Research Part II: Topical Studies in Oceanography 58 (3–4), 296-310. http://dx.doi.org/10.1016/j.dsr2.2010.08.009.
Kelley, D.S., Carbotte, S.M., Caress, D.W., Clague, D.A., Delaney, J.R., Gill, J.B., Hadaway, H., Holden, J.F., Hooft, E.E., Kellogg, J.P., 2012. Endeavour Segment of the Juan de Fuca Ridge: One of the most remarkable places on Earth. Oceanography, 25(1), 44-61.
Kwon, E.Y., Kim, G., Primeau, F., Moore, W.S., Cho, H.-M., DeVries, T., Sarmiento, J.L., Charette, M.A., Cho, Y.-K., 2014. Global estimate of submarine groundwater discharge based on an observationally constrained radium isotope model. Geophysical Research Letters, 2014GL061574. 10.1002/2014GL061574.

Lacan, F., Jeandel, C., 2001. Tracing Papua New Guinea imprint on the central Equatorial Pacific Ocean using neodymium isotopic compositions and Rare Earth Element patterns. Earth and Planetary Science Letters 186 (3-4), 497-512.

Lam, P.J., Bishop, J.K.B., Henning, C.C., Marcus, M.A., Waychunas, G.A., Fung, I.Y., 2006. Wintertime phytoplankton bloom in the subarctic Pacific supported by continental margin iron. Global Biogeochemical Cycles 20 (1), doi:10.1029/2005GB002557.

Lam, P.J., Marchal, O., 2015. Insights into Particle Cycling from Thorium and Particle Data. Annual Review of Marine Science 7 (1), 159-184. doi:10.1146/annurev-marine-010814-015623.

Lam, P.J., Ohnemus, D.C., Auro, M.E., 2015a. Size-fractionated major particle composition and concentrations from the US GEOTRACES North Atlantic Zonal Transect. Deep Sea Research Part II: Topical Studies in Oceanography 116 (0), 303-320. http://dx.doi.org/10.1016/j.dsr2.2014.11.020.

Lam, P.J., Twining, B.S., Jeandel, C., Roychoudhury, A., Resing, J.A., Santschi, P.H., Anderson, R.F., 2015b. Methods for analyzing the concentration and speciation of major and trace elements in marine particles. Progress in Oceanography 133, 32-42. http://dx.doi.org/10.1016/j.pocean.2015.01.005.

Lamborg, C.H., Hammerschmidt, C.R., Bowman, K.L., Swarr, G.J., Munson, K.M., Ohnemus, D.C., Lam, P.J., Heimburger, L.-E., Rijkenberg, M.J.A., Saito, M.A., 2014. A global ocean inventory of anthropogenic mercury based on water column measurements. Nature 512 (7512), 65-68. doi: 10.1038/nature13563.

Lerner, P., Marchal, O., Lam, P.J., Anderson, R.F., Buesseler, K., Charette, M.A., Edwards, R.L., Hayes, C.T., Huang, K.-F., Lu, Y., Robinson, L.F., Solow, A., 2016. Testing models of thorium and particle cycling in the ocean using data from station GT11-22 of the U.S. GEOTRACES North Atlantic section. Deep Sea Research Part I: Oceanographic Research Papers 113, 57-79. http://dx.doi.org/10.1016/j.dsr.2016.03.008.

Lippiatt, S.M., Brown, M.T., Lohan, M.C., Bruland, K.W., 2011. Reactive iron delivery to the Gulf of Alaska via a Kenai eddy. Deep Sea Research Part I: Oceanographic Research Papers 58 (11), 1091-1102. http://dx.doi.org/10.1016/j.dsr.2011.08.005.

Lippiatt, S.M., Lohan, M.C., Bruland, K.W., 2010. The distribution of reactive iron in northern Gulf of Alaska coastal waters. Marine Chemistry 121 (1-4), 187-199.

Lodge, M., Johnson, D., Le Gurun, G., Wengler, M., Weaver, P., Gunn, V., 2014. Seabed mining: International Seabed Authority environmental management plan for the Clarion–Clipperton Zone. A partnership approach. Marine Policy 49, 66-72. http://dx.doi.org/10.1016/j.marpol.2014.04.006.

Lupton, J., 1998. Hydrothermal helium plumes in the Pacific Ocean. Journal of Geophysical Research: Oceans 103 (C8), 15853-15868. 10.1029/98JC00146.

Lupton, J.E., Craig, H., 1981. A major He-3 source at 15-degrees-S on the East Pacific Rise. Science 214, 13-18.

Lupton, J.E., Weiss, R.F., Craig, H., 1977. Mantle helium in hydrothermal plumes in the Galapagos Rift. Nature 267 (5612), 603-604.

Maldonado, M.T., Price, N.M., 1999. Utilization of iron bound to strong organic ligands by plankton communities in the subarctic Pacific Ocean. Deep Sea Research Part II: Topical Studies in Oceanography 46 (11-12), 2447-2473.

Marchal, O., Lam, P.J., 2012. What can paired measurements of Th isotope activity and particle concentration tell us about particle cycling in the ocean? Geochimica Et Cosmochimica Acta 90 (0), 126-148. doi: 10.1016/j.gca.2012.05.009.

Marconi, D., Alexandra Weigand, M., Rafter, P.A., McIlvin, M.R., Forbes, M., Casciotti, K.L., Sigman, D.M., 2015. Nitrate isotope distributions on the US GEOTRACES North Atlantic cross-basin section: Signals of polar nitrate sources and low latitude nitrogen cycling. Marine Chemistry 177, Part 1, 143-156. http://dx.doi.org/10.1016/j.marchem.2015.06.007.

Martin, J.H., 1990. Glacial-interglacial CO_2 change: the iron hypothesis. Paleoceanography 5 (1), 1-13.

Matsumoto, K., 2007. Radiocarbon-based circulation age of the world oceans. Journal of Geophysical Research: Oceans 112 (C9), n/a-n/a. 10.1029/2007JC004095.

McDonnell, A.M.P., Lam, P.J., Lamborg, C.H., Buesseler, K.O., Sanders, R., Riley, J.S., Marsay, C., Smith, H.E.K., Sargent, E.C., Lampitt, R.S., Bishop, J.K.B., 2015. The oceanographic toolbox for the collection of sinking and suspended marine particles. Progress in Oceanography 133, 17-31. http://dx.doi.org/10.1016/j.pocean.2015.01.007.

Milne, A., Landing, W., 2008. Distributions of Eight Trace Elements From a North-South Transect of the Pacific Ocean During the CLIVAR/Repeat Hydrography P16S and P16N Cruises. AGU Fall Meeting Abstracts, p. 1117.

Moffett, J.W., Dupont, C., 2007. Cu complexation by organic ligands in the sub-arctic NW Pacific and Bering Sea. Deep Sea Research Part I: Oceanographic Research Papers 54 (4), 586-595.

Moffett, J., German, C., 2009. U.S. GEOTRACES Pacific Implementation Workshop Report. http://www.usgeotraces.com/documents/pacificDOC/Pacific_Report_Jun09_000.pdf.

Moffett, J.W., Goepfert, T.J., Naqvi, S.W.A., 2007. Reduced iron associated with secondary nitrite maxima in the Arabian Sea. Deep Sea Research Part I: Oceanographic Research Papers 54 (8), 1341-1349. 10.1016/j.dsr.2007.04.004.

Moore, J.K., Doney, S.C., 2007. Iron availability limits the ocean nitrogen inventory stabilizing feedbacks between marine denitrification and nitrogen fixation. Global Biogeochemical Cycles 21 (2), n/a-n/a. 10.1029/2006GB002762.

Murray, J.W., Johnson, E., Garside, C., 1995. A U.S. JGOFS process study in the equatorial Pacific (EqPac): Introduction. Deep Sea Res. II, 42, 275-293.

Noble, A.E., Echegoyen-Sanz, Y., Boyle, E.A., Ohnemus, D.C., Lam, P.J., Kayser, R., Reuer, M., Wu, J., Smethie, W., 2015. Dynamic variability of dissolved Pb and Pb isotope composition from the U.S. North Atlantic GEOTRACES transect. Deep Sea Research Part II: Topical Studies in Oceanography 116, 208-225. http://dx.doi.org/10.1016/j.dsr2.2014.11.011.

Noble, A.E., Lamborg, C.H., Ohnemus, D.C., Lam, P.J., Goepfert, T.J., Measures, C.I., Frame, C.H., Casciotti, K.L., DiTullio, G.R., Jennings, J., Saito, M.A., 2012. Basin-scale inputs of cobalt, iron, and manganese from the Benguela-Angola front to the South Atlantic Ocean. Limnology and Oceanography 57 (4), 989-1010. 10.4319/lo.2012.57.4.0989.

Nowicki, J.L., Johnson, K.S., Coale, K.H., Elrod, V.A., Lieberman, S.H., 1994. Determination of Zinc in Seawater Using Flow Injection Analysis with Fluorometric Detection. Analytical Chemistry 66 (17), 2732-2738. 10.1021/ac00089a021.

Ohnemus, D.C., Lam, P.J., 2015. Cycling of lithogenic marine particles in the US GEOTRACES North Atlantic transect. Deep Sea Res. II, 116: 283-302. http://dx.doi.org/10.1016/j.dsr2.2014.11.019.

Owens, S.A., Pike, S., and Buesseler, K.O. 2015. Thorium-234 as a tracer of particle dynamics and upper ocean export in the Atlantic Ocean. Deep Sea Res. II, 116: 42-59.

Peters, B., K.L. Casciotti, W. Jenkins, J. Swift, C.R. German, J. Moffett, G. Cutter, and M. Brzezinski. Water mass analysis of the 2013 US GEOTRACES Eastern Pacific Zonal Transect (GP16). In preparation for Marine Chemistry.

Piepgras, D.J., Jacobsen, S.B., 1988. The isotopic composition of neodymium in the North Pacific. Geochim. Cosmochim. Acta, 52, 1373-1381.

Ranville, M.A., Cutter, G.A., Buck, C.S., Landing, W.M., Cutter, L.S., Resing, J.A., Flegal, A.R., 2010. Aeolian Contamination of Se and Ag in the North Pacific from Asian Fossil Fuel Combustion. Environmental Science & Technology 44 (5), 1587-1593. 10.1021/es902523m.

Reid, J.L., 1997. On the total geostrophic circulation of the Pacific Ocean: Flow patterns, tracers, and transports. Progress in Oceanography 39 (4), 263-352.

Resing, J.A., Sedwick, P.N., German, C.R., Jenkins, W.J., Moffett, J.W., Sohst, B.M., Tagliabue, A., 2015. Basin-scale transport of hydrothermal dissolved metals across the South Pacific Ocean. Nature 523 (7559), 200-203. 10.1038/nature14577.

Revels, B.N., Ohnemus, D.C., Lam, P.J., Conway, T.M., John, S.G., 2015. The isotopic signature and distribution of particulate iron in the North Atlantic Ocean. Deep Sea Research Part II: Topical Studies in Oceanography 116, 321-331. http://dx.doi.org/10.1016/j.dsr2.2014.12.004.

Roden, G.I., 1991. Subarctic-subtropical transition zone of the North Pacific: large-scale aspects and mesoscale structure. NOAA Tech. Rep. NMFS 105, 1-38.Saito, M.A., Moffett, J.W., 2001. Complexation of cobalt by natural organic ligands in the Sargasso Sea as determined by a new high-sensitivity electrochemical cobalt speciation method suitable for open ocean work. Marine Chemistry 75 (1-2), 49-68.

Rue, E.L., Bruland, K.W., 1997. The role of organic complexation on ambient iron chemistry in the equatorial Pacific Ocean and the response of a mesoscale iron addition experiment. Limnology and Oceanography 42 (5), 901-910.

Saito, M.A., Moffett, J.W., 2001. Complexation of cobalt by natural organic ligands in the Sargasso Sea as determined by a new high-sensitivity electrochemical cobalt speciation method suitable for open ocean work. Marine Chemistry 75 (1-2), 49-68.

Saito, M.A., Noble, A.E., Tagliabue, A., Goepfert, T.J., Lamborg, C.H., Jenkins, W.J., 2013. Slow-spreading submarine ridges in the South Atlantic as a significant oceanic iron source. Nature Geosci advance online publication. 10.1038/ngeo1893
http://www.nature.com/ngeo/journal/vaop/ncurrent/abs/ngeo1893.html - supplementary-information.

Sanders, J.G., 1979. Effects of arsenic speciation and phosphate concentration on arsenic inhibition of skeletonema costatum (bacillariophyceae) 1. Journal of Phycology 15 (4), 424-428.

Schlitzer, R., 2015. *eGEOTRACES* - Electronic Atlas of GEOTRACES Sections and Animated 3D Scenes, http://www.egeotraces.org**.**

Schlitzer, R. 2016. Quantifying He fluxes from the mantle using multi-tracer data assimilation. Philosophical Transactions of the Royal Society A.In press

Sholkovitz, E.R., Elderfield, H., Szymczak, R., Casey, K., 1999. Island weathering: river sources of rare earth elements to the Western Pacific Ocean. Marine Chemistry 68 (1-2), 39-57.

Sigman DM, DiFiore PJ, Hain MP, Deutsch C, Wang Y, Karl DM, et al. 2009. The dual isotopes of deep nitrate as a constraint on the cycle and budget of oceanic fixed nitrogen. Deep Res I, 56(9):1419–1439.

Sigman, D.M., Haug, G.H. 2003. The biological pump in the past. Treatise on Geochemistry, in *The Oceans and Marine Geochemistry, Treatise on Geochemistry* 6: 491-528

Sigman DM, Robinson R, Knapp AN, van Geen A, McCorkle DC, Brandes JA, Thunell, R.C.. 2003. Distinguishing between water column and sedimentary denitrification in the Santa Barbara Basin using the stable isotopes of nitrate. Geochem. Geophys. Geosys., 4, 1040, doi:10.1029/2002GC000384

Sinoir, M., Butler, E.C.V., Bowie, A.R., Mongin, M. Nesterenko, P.N., and Hassler, C.S. 2011. Zinc marine biogeochemistry in seawater: a review. Mar. Freshwater Res., 63: 644-657.

Slemons, L.O., Murray, J.W., Resing, J., Paul, B., Dutrieux, P., 2010. Western Pacific coastal sources of iron, manganese, and aluminum to the Equatorial Undercurrent. Global Biogeochemical Cycles 24 (3), n/a-n/a. 10.1029/2009GB003693.

Sunda, W., 2012. Feedback interactions between trace metal nutrients and phytoplankton in the ocean. Frontiers in Microbiology 3. 10.3389/fmicb.2012.00204.

Tagliabue, A., Aumont, O., DeAth, R., Dunne, J.P., Dutkiewicz, S., Galbraith, E., Misumi, K., Moore, J.K., Ridgwell, A., Sherman, E., Stock, C., Vichi, M., Völker, C., Yool, A., 2016. How well do global ocean biogeochemistry models simulate dissolved iron distributions? Global Biogeochemical Cycles 30 (2), 149-174. 10.1002/2015GB005289.

Tagliabue, A., Bopp, L., Dutay, J.-C., Bowie, A.R., Chever, F., Jean-Baptiste, P., Bucciarelli, E., Lannuzel, D., Remenyi, T., Sarthou, G., Aumont, O., Gehlen, M., Jeandel, C., 2010. Hydrothermal contribution to the oceanic dissolved iron inventory. Nature Geoscience 3, 252-256.

Tagliabue, A., Williams, R.G., Rogan, N., Achterberg, E.P., Boyd, P.W., 2014. A ventilation-based framework to explain the regeneration-scavenging balance of iron in the ocean. Geophysical , 63:Research Letters, 2014GL061066. 10.1002/2014GL061066.

Talley, L.D., 1993. Distribution and Formation of North Pacific Intermediate Water. Journal of Physical Oceanography 23 (3), 517-537. 10.1175/1520-0485(1993)023<0517:dafonp>2.0.co;2.

Talley, L.D., Pickard, G.L., Emery, W.J., Swift, J.H., 2011. *Descriptive physical oceanography: an introduction*. Academic Press.

Toggweiler JR, Dixon K, Broecker WS. 1991. The Peru Upwelling and the Ventilation of the South-Pacific Thermocline. J Geophys Res. 96(C11):20467–97.

Toner, B.M., Fakra, S.C., Manganini, S.J., Santelli, C.M., Marcus, M.A., Moffett, J.W., Rouxel, O., German, C.R. and Edwards, K.J., 2009. Preservation of iron (II) by carbon-rich matrices in a hydrothermal plume..Nature Geoscience, *2*(3),197-201.

Tsuchiya, M., 1972. A subsurface north equatorial countercurrent in the eastern Pacific Ocean. J. Geophys. Res., 77, 5981-5986.

Tsuchiya, M., 1975. Subsurface countercurrents in the eastern equatorial Pacific Ocean. J. Mar. Res., 33, 145-175.

Twining, B.S., Baines, S.B., 2013. The Trace Metal Composition of Marine Phytoplankton. Annual Review of Marine Science 5 (1), 191-215. doi:10.1146/annurev-marine-121211-172322.

Twining, B.S., Nodder, S.D., King, A.L., Hutchins, D.A., LeCleir, G.R., DeBruyn, J.M., Maas, E.W., Vogt, S., Wilhelm, S.W., Boyd, P.W., 2014. Differential remineralization of major and trace elements in sinking diatoms. Limnology and Oceanography 59 (3), 689-704.

Twining, B.S., Rauschenberg, S., Morton, P.L., Ohnemus, D.C., Lam, P.J., 2015. Comparison of particulate trace element concentrations in the North Atlantic Ocean as determined with discrete bottle sampling and in situ pumping. Deep Sea Research Part II: Topical Studies in Oceanography 116, 273-282. http://dx.doi.org/10.1016/j.dsr2.2014.11.005.

Vink, S., Boyle, E.A., Measures, C.I., Yuan, J., 2000. Automated high resolution determination of the trace elements iron and aluminium in the surface ocean using a towed fish coupled to flow injection analysis. Deep-Sea Research Part I-Oceanographic Research Papers 47 (6), 1141-1156.

Wedding, L.M., Friedlander, A.M., Kittinger, J.N., Watling, L., Gaines, S.D., Bennett, M., Hardy, S.M., Smith, C.R., 2013. From principles to practice: a spatial approach to systematic conservation planning in the deep sea. Proceedings of the Royal Society of London B: Biological Sciences 280 (1773).

Wu, J., Aguilar-Islas, A., Rember, R., Weingartner, T., Danielson, S., Whitledge, T., 2009. Size-fractionated iron distribution on the northern Gulf of Alaska. Geophys. Res. Lett. 36 (11), L11606. 10.1029/2009gl038304.

Wyatt, N.J., Milne, A., Woodward, E.M.S., Rees, A.P., Browning, T.J., Bouman, H.A., Worsfold, P.J., Lohan, M.C., 2014. Biogeochemical cycling of dissolved zinc along the GEOTRACES South Atlantic transect GA10 at 40°S. Global Biogeochemical Cycles 28 (1), 44-56. 10.1002/2013GB004637.

Wyrtki, K., 1975. El Niño—The Dynamic Response of the Equatorial Pacific Oceanto Atmospheric Forcing. Journal of Physical Oceanography 5 (4), 572-584. doi:10.1175/1520-0485(1975)005<0572:ENTDRO>2.0.CO;2.

Wyrtki, K., Kilonsky, B., 1984. Mean Water and Current Structure during the Hawaii-to-Tahiti Shuttle Experiment. Journal of Physical Oceanography 14 (2), 242-254. doi:10.1175/1520-0485(1984)014<0242:MWACSD>2.0.CO;2.

Zhang, J.-Z., 2000. Shipboard automated determination of trace concentrations of nitrite and nitrate in oligotrophic water by gas-segmented continuous flow analysis with a liquid waveguide capillary flow cell. Deep Sea Research Part I: Oceanographic Research Papers 47 (6), 1157-1171. http://dx.doi.org/10.1016/S0967-0637(99)00085-0.

Zimmer, L.A. and G. A. Cutter. 2012. High resolution determination of nanomolar concentrations of dissolved reactive phosphate in ocean surface waters using long path liquid waveguide capillary cells (LWCC) and spectrometric detection. Limnol. Oceanogr. Methods, 10:568-580.