PROJECT SUMMARY

Overview:

We propose a GEOTRACES research cruise from Tahiti to Chile (GP17-OCE) that enables sampling for a broad suite of trace elements and isotopes (TEI) across oceanographic regions of importance to global nutrient and carbon cycling. The proposed cruise would cross the South Pacific Gyre, the Antarctic Circumpolar Current, iron-limited Antarctic waters, and the Chilean margin. In combination with a proposed companion GEOTRACES cruise on a research icebreaker (GP17-ANT) that would be joined by two overlapping stations, we would create an ocean section from the ocean's most oligotrophic waters to its highly-productive Antarctic polar region. The cruise would support and provide management infrastructure for individual science projects focused on measuring the external fluxes and internal cycling of TEIs along this section. This management proposal has several objectives: 1) plan and coordinate a 55-day research cruise in 2021-2022; 2) use both conventional and trace-metal 'clean' sampling systems to obtain TEI samples, as well as facilitate sampling for atmospheric aerosols and large volume particles and radionuclides; 3) acquire hydrographic data and samples for salinity, dissolved oxygen, algal pigments, and macronutrients; and deliver these data to relevant repositories; 4) ensure that proper QA/QC protocols are followed and reported, as well as GEOTRACES intercalibration protocols; 5) prepare the final cruise report to be posted with data; 6) coordinate between all funded cruise investigators, as well as with leaders of proposed GP17-ANT cruise; and 7) conduct broader impact efforts that will engage the public in oceanographic research using immersive technology.

Intellectual Merit:

The South Pacific Gyre and Pacific sector of the Southern Ocean play critical roles in global water mass circulation and associated global transfer of heat, carbon, and nutrients, but they are chronically understudied for TEIs due to their remote locale. These are regions of strong, dynamic fronts where sub-surface water masses upwell and subduct, and biological and chemical processes in these zones determine nutrient stoichiometries and tracer concentrations in waters exported to lower latitudes. The Pacific sector represents an endmember of extremely low external TEI surface fluxes and thus an important region to constrain inputs from the rapidly-changing Antarctic continent. Compared to other ocean basins, TEI cycling in the these regions is thought to be dominated by internal cycling processes such as biological uptake, regeneration, and scavenging, and these are poorly represented in global ocean models. The cruise will enable funded investigators to address research questions such as: 1) what are relative rates of external TEI fluxes to this region, including dust, sediment, hydrothermal, and cryospheric fluxes? 2) What are the micro(nutrient) regimes that support productivity, and what impacts do biomass accumulation, export, and regeneration have on TEI cycling and stoichiometries of exported material? 3) What are TEI and nutrient stoichiometries of subducting water masses, and how do scavenging and regeneration impact these during transport northward?

Broader Impacts:

The Southern Ocean is revealing changing physics and biogeochemistry that will impact heat, carbon, and nutrient cycles globally, and oligotrophic conditions represented in the South Pacific Gyre are predicted to expand. However, these regions are undersampled. Thus, the results generated by this proposed cruise will significantly impact global biogeochemical understanding. The motivations for and at-sea challenges of this work will be communicated to the general public through creation of immersive 360/Virtual Reality experiences, via a collaboration with Texas A&M University Visualization LIVE Lab. Through Virtual Reality, users will experience firsthand what life and TEI data collection at sea entail. Virtual reality/digital games and 360 experiences will be distributed through GEOTRACES outreach websites, through PI engagement with local schools, libraries, STEM summer camps, and adult service organizations, and through a collaboration with the National Academy of Sciences.

INTELLECTUAL MERIT

1. Introduction

Trace elements and their isotopes (TEIs) play key roles as micronutrients for marine organisms (Morel and Price, 2003), potentially toxic contaminants (e.g., Mann et al., 2002), and tracers of both modern and past ocean processes (e.g., Anderson et al., 2014; Henderson, 2002). TEIs occur at trace concentrations (nano- to picomolar) and are frequently prone to contamination during sampling and analysis, as well as suffering challenging analytical interferences. Given these complexities, a coordinated global sampling approach was developed by GEOTRACES, an international program to study the biogeochemical cycles of TEIs in the ocean (GEOTRACES, 2006). GEOTRACES sampling activities are focused on constraining inputs and sinks of TEIs across ocean interfaces, as well as understanding the processes that influence the internal cycling of TEIs in the ocean (**Fig. 1**). *Here we propose a new GEOTRACES section to the South Pacific and Southern Ocean (GP17) in a unique region of low external fluxes, strong internal TEI cycling, and intermediate water mass formation regions of global relevance.*

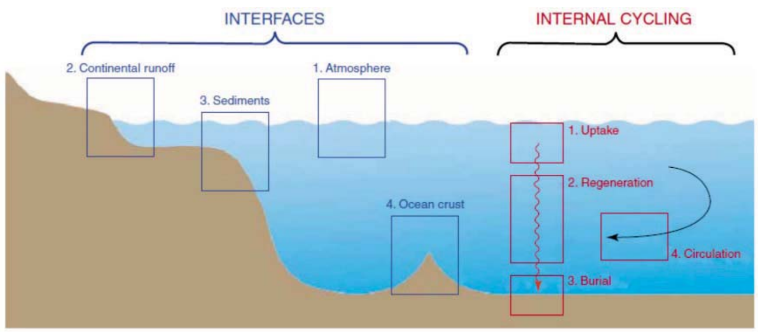

Fig. 1. Schematic of GEOTRACES approach to studying TEI fluxes across interfaces and within internal cycles and circulation.

U.S. GEOTRACES cruises thus far have significantly advanced understanding of TEI ***fluxes*** to ocean basins. Significant external inputs of Fe to the Atlantic from Saharan dust, margin sediments, and hydrothermal vents have been quantified (Conway and John, 2014; Hatta et al., 2015). Mercury inventories from GEOTRACES cruises show that nearly 58 million kilograms of anthropogenic Hg are now present in the ocean, mostly in the upper 1000 m (Lamborg et al., 2014). In the South Pacific, the 2013 GEOTRACES GP16 zonal cruise revealed that hydrothermal inputs of Fe and other metals are transported thousands of kilometers at depth, significantly increasing the importance of this global micronutrient source (Fitzsimmons et al., 2017; Resing et al., 2015). Synthesis tools developed during GEOTRACES such as coupling trace metal and radioisotope tracer data to derive fluxes (e.g., Charette et al., 2016) have documented increased fluxes of shelf-derived materials to the Arctic Ocean (Kipp et al., 2018) and constrained atmospheric dust inputs to the North Atlantic (e.g., Anderson et al., 2016) and Arctic (e.g., Kadko et al., 2019; Marsay et al., 2018).

Data from GEOTRACES section cruises are also transforming our understanding of the ***internal cycling*** of TEIs. GEOTRACES data have shown the importance of organic ligands for stabilizing dissolved Fe (e.g., Buck et al., 2016; Buck et al., 2015), as well as the controlling influence of biological processes on Fe cycling (Tagliabue et al., 2017). Differential uptake and regeneration of the micronutrients Fe, Zn, Co, and Cd have been demonstrated by integrating GEOTRACES data with global biogeochemical models (e.g., Boyd et al., 2017; Roshan et al., 2018; Roshan and Wu, 2015; Saito et al., 2017). Abiotic scavenging of metals – long recognized but difficult to measure directly – has been quantified from a range of dissolved and particulate TEI measurements combined with radionuclides (Hayes et al., 2018b; Jacquot and Moffett, 2015; Ohnemus et al., 2019; Pavia et al., 2019), and this process has been shown to exert controls on the fate of Fe (Tagliabue et al., 2019) and Zn (Weber et al., 2018) in the deep ocean. As the GEOTRACES program has accumulated high-quality TEI data on a global scale, the program has evolved towards more challenging chemical tracer goals of quantifying rates of internal cycling processes, especially in synthesis efforts across multiple GEOTRACES sections.

2. The GP17 section

The South Pacific and Southern Oceans play critical roles in global water mass circulation and associated global transfer of heat and nutrients (Marinov et al., 2006), but they are chronically understudied for TEIs due to their remote locale. In order to characterize TEI cycling in these regions and their impact on global biogeochemistry, we propose a GEOTRACES section cruise (GP17) from Tahiti to Antarctica, also sampling along the Amundsen Sea sector of the Antarctic continental margin, and finally encompassing a shorter section toward the continental margin of southern Chile (**Fig. 2**). *TEI availability influences productivity in this region, which sets nutrient delivery to lower latitudes (Sarmiento et al., 2004a) and is likely impacted by changing Antarctic and climate conditions (Martínez-García et al., 2014), making this a key region to constrain TEI biogeochemistry with a GEOTRACES cruise.* Logistical constraints dictate that two cruises will be needed to complete the proposed GP17 transect at the required sampling resolution of the International GEOTRACES program: one cruise sampling the deep ocean stations using a Global-class ship ("GP17-OCE"), and the other cruise sampling the Antarctic continental margin using a research icebreaker ("GP17-ANT"). ***This proposal is for the management and implementation of the GP17-OCE cruise, with the scientific motivations presented below.***

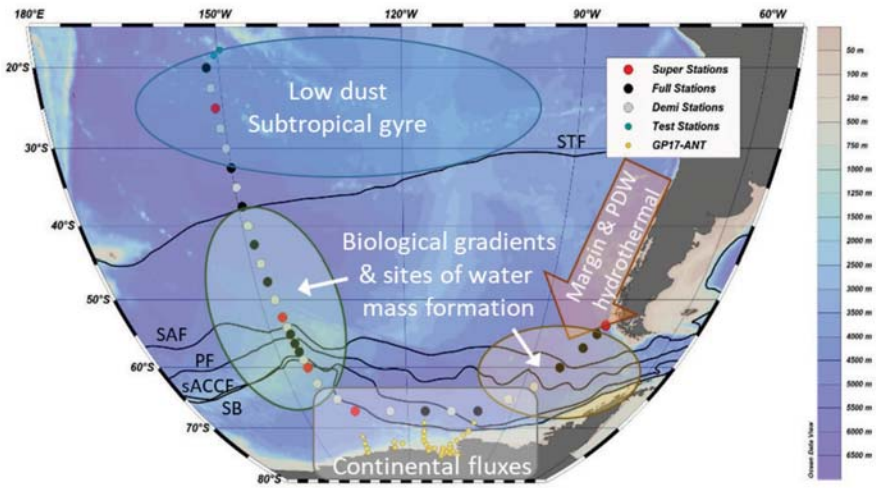

Fig. 2. GP17-OCE proposed cruise track, including oceanographic fronts and zones (Orsi et al. 1995). Also shown are stations of the partner GP17-ANT cruise (yellow) and major biogeochemical features of interest.

3. GP17 physical circulation

Hydrography and circulation set first order constraints on the distribution of trace elements and isotopes in the ocean, and GP17-OCE will cross major fronts and sample many water masses in the South Pacific. While these have been called various names in past studies, we use here the water mass nomenclature of Talley et al. (2011) for consistency with **Fig. 3**. Along the southbound **meridional section,** the South Pacific's anticyclonic subtropical gyre (SPG) dominates circulation through 400 m and is composed of warm, salty Subtropical Surface Water (STSW). The southern border of the SPG is the Subtropical Front (STF), typically 30-40°S (**Fig. 2**). South of the STF, colder and fresher Subantarctic Surface Water (SASW) is the dominant water mass until the frontal region of the Antarctic Circumpolar Current (ACC), which is composed of three eastward-flowing zonal jets: the Subantarctic Front (SAF), the Polar Front (PF), and the southern ACC Front (sACCF; Orsi et al., 1995). These 10-70 cm/s zonal jets are driven by unobstructed westerly winds and extend from the surface to the bottom, with significant meridional eddy transport between the fronts (Rintoul, 2018; Talley et al., 2011). Surface waters of the ACC are composed of Antarctic Surface Water (AASW), and the Southern Boundary marks the transition from the ACC region to the Subpolar Region, which includes the cyclonic Ross gyre and the Antarctic continental shelf regions that will be explored on GP17-ANT. A short eastbound **zonal section** will traverse 67˚S, crossing regions of upwelled Circumpolar Deep Water (CDW), as well as the southern ACC fronts. A final **margin section** will then approach South America, crossing a zone of intense intermediate water formation and the deep, southward flow of Pacific Deep Water (PDW) into the Southern Ocean, as well as TEI sources and sinks on the Chilean margin.

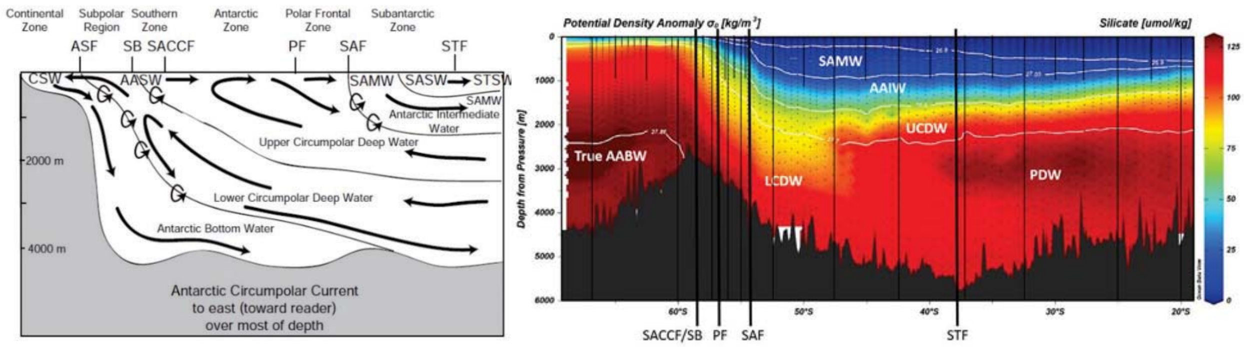

Fig. 3. left) Schematic of currents and water masses around ACC region (Talley et al., 2011). right) Section of silicate (colors) and potential density anomaly (contours) along 150˚W from GO-SHIP P16S in 2014. Fronts and station locations are indicted with thick and thin black lines, respectively.

The ACC frontal region is critical to global circulation, with 80% of global deep waters surfacing in the ACC, forming the critical return leg of global overturning circulation (Lumpkin and Speer, 2007; Talley, 2013). Global intermediate and deep water masses are also subducted in the ACC region and then travel northward along isopycnals, reaching the northern hemisphere (**Fig. 3**). Subantarctic Mode Water (SAMW) forms in the Subantarctic Zone (SAZ) in spring when deep winter mixed layers are capped by surface warming and then subducted in a thick subsurface layer. One "hotspot" of SAMW formation is the South Pacific along the GP17 margin section (Herraiz-Borreguero and Rintoul, 2011), which then moves anticyclonically throughout the South Pacific. Thus, SAMW has massive volume and carries enrichments in atmospherically-derived anthropogenic CFCs and CO_2 across the Pacific (Khatiwala et al., 2013; Willey et al., 2004). It also carries unique nutrient stoichiometry (Sarmiento et al., 2004a), with abundant nitrate but minimal silicate that creates a negative Si* (= [Si] – [nitrate]) that can be used to track SAMW circulation (**Figs. 3, 6B**). Below SAMW, Antarctic Intermediate Water (AAIW) can be identified in the 500-1500 m depth range as a layer of minimum salinity (**Fig. 3**). AAIW is thought to form just north of the PF in the far southeast Pacific immediately west of the Drake Passage (Piola and Georgi, 1982) and then to subduct at the SAF to extend as far north as 10-20°N in the Pacific and Atlantic. AAIW follows an anticyclonic circulation in the South Pacific (Tomczak and Godfrey, 2003) that results in more aged AAIW in the west (near GP17 meridional section) than in the east (margin section). Thus, GP17-OCE is an ideal transect to use CFC age, AOU, and elemental relationships for tracing regeneration and/or scavenging timescales within the globally-relevant AAIW water mass.

Below AAIW lies CDW, which is a mixture of North Atlantic Deep Water, Indian Deep Water, and Pacific Deep Water (PDW) that mix in the deep waters of the ACC frontal region to create CDW (Sarmiento et al., 2004a). CDW is divided into Upper Circumpolar Deep Water (UCDW), with minimal oxygen and high Si that upwells south of the PF, and higher-salinity Lower Circumpolar Deep Water (LCDW). Recent advances from the Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM) project have shown that CDW upwelling occurs at localized "hotspots" associated with bathymetric highs along the ACC (Tamsitt et al., 2017), aided by eddy mixing near the surface (Sallée et al., 2010; Tamsitt et al., 2018). GP17-OCE will encounter two of these CDW upwelling "hotspots" – one at ~145°W, where the Pacific-Antarctic Ridge guides the ACC fronts northward to stimulate upwelling, and the second near the Drake Passage – enabling the assessment of these hotspots as agents of significant TEI flux. Finally, GP17-OCE will also sample LCDW that is called in most oceanographic contexts "Antarctic Bottom Water" (AABW), which fills in bottom waters of the entire Pacific Ocean, as well as denser "true AABW" that is kept south of the ACC by the Pacific-Antarctic Ridge **(Fig. 3)**.

As noted above, *many of the intermediate and deep water masses that fill the global ocean are formed around Antarctica. Consequently, determining how upper ocean biogeochemical processes* *imprint preformed nutrient and tracer concentrations onto these water masses is key to understanding impacts on circulation tracers and nutrient delivery to the lower latitudes, not only into the Pacific but across the entire global ocean.* GP17-OCE will sample these water masses at their formation sites in order to track conservative mixing and trace non-conservative changes to TEIs in these subsurface water masses downstream (Middag et al., 2018; Roshan et al., 2018; Weber et al., 2018).

4. GP17-OCE Biogeochemical Motivations

The GP17-OCE cruise has been designed to study feedbacks between external TEI fluxes and internal biogeochemistry in the context of the globally-relevant physical circulation just described. While previous U.S. GEOTRACES cruises targeted regions of uniquely high external TEI fluxes, the South Pacific and Southern Ocean represent an endmember of extremely low dust flux to surface waters (Albani et al., 2014). GP17-OCE will also characterize the influence of the rapidly changing Antarctic continent and the physical upwelling of deep waters to the largest Fe-limited HNLC region (e.g., Martin et al., 1990; Moore et al., 2002). Thus, *GP17-OCE provides an ideal opportunity to study biogeochemical controls on TEI cycling and the intimately linked impacts of these biogeochemical processes on water mass chemistry, within a zone of unparalleled influence on global carbon and climate dynamics.* The cruise proposed here will enable funded investigators to address research questions such as:

A. **What are the relative rates of external TEI fluxes to the South Pacific Ocean and Southern Ocean, including dust, sediment, hydrothermal, and cryospheric fluxes?**
B. **What are the (micro)nutrient regimes that support observed gradients in productivity and community composition across the South Pacific gyre, ACC fronts, and Antarctic Zone? What impacts do biomass accumulation, export, and regeneration have on TEI cycling in these regions, and what are the elemental stoichiometries of exported material?**
C. **What are TEI and macronutrient stoichiometries of the upwelling and subducting water masses that influence the global ocean at intermediate to abyssal depths? How do scavenging and regeneration alter these stoichiometries during transport northward?**

A. External TEI fluxes

The South Pacific Ocean represents an extreme low-flux endmember of external TEI inputs to surface waters of the global ocean. This is largely due to the vanishingly low dust fluxes to the South Pacific, which have been observed to be 1-2 orders of magnitude lower in Fe flux than to the North Pacific (**Fig. 4b**), Atlantic, and Indian Oceans (Albani et al., 2014). The South Pacific is also uniquely dominated by wet deposition, especially in the Western Pacific nearer our meridional section (Wagener et al., 2008). Thus the South Pacific would especially benefit from GEOTRACES-style simultaneous characterization of aerosol and rain water composition (e.g., Buck et al., 2019; Marsay et al., 2018; Shelley et al., 2018; Shelley et al., 2015), quantification of dust flux using the GEOTRACES suite of tracers (e.g., Anderson et al., 2016), and direct measurement of vertical diffusivity using ^{7}Be (Kadko, 2017) that would allow the role of wet/dry deposition to be quantified in metal and carbon budgets of this low-dust endmember of the global ocean.

Studies to date generally conclude that aerosol deposition is insufficient to support observed trace metal inventories of the South Pacific euphotic zone, which appear to be dominated instead by horizontal fluxes and vertical mixing from below (Ellwood et al., 2018; Fitzsimmons et al., 2016; Sanial et al., 2018). Nutricline metals in the South Pacific appear to be largely sourced from margin sediments (**Fig. 4a**), despite continents situated thousands of kilometers from the central Pacific. However there are hints that dust can be a significant flux at some longitudes in the western Pacific (Buck et al., 2019; Ellwood et

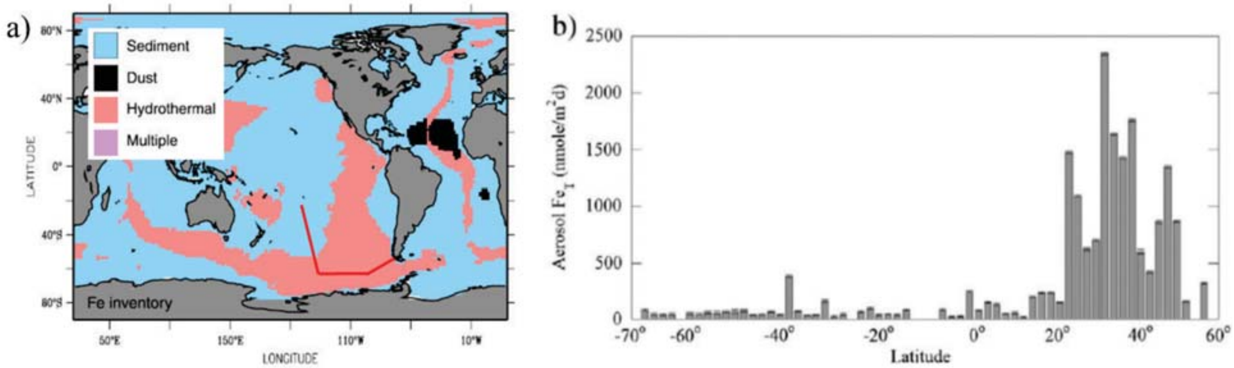

Fig. 4. A) Estimated sources of Fe to South Pacific and Southern Ocean (Tagliabue et al., 2014). B) Meridional gradient in aerosol Fe sources to the Pacific Ocean (Buck et al., 2013).

al., 2018), and recent work concludes that in fact dust is the dominant source of Fe to the SPG (Pavia et al., submitted). Indeed, quantification of micronutrient TEI fluxes is a major goal of the multi-tracer GEOTRACES approach and will be especially critical for margin-derived TEIs on the remote meridional section of GP17-OCE, as well as the margin section near South America. Highly elevated concentrations of dissolved Fe, Mn, and Al in continental shelf waters of the Drake Passage (Klunder et al., 2014; Middag et al., 2012) suggest that we will capture continental shelf inputs upstream in the Cape Horn Current on the GP17-OCE margin section (Silva et al., 2009), especially given the relatively wide continental shelf of our transect, as wide shelves are thought to support upwelling of margin TEIs in the Southeast Pacific (Bruland et al., 2005). Radium isotopes have been utilized successfully on prior U.S. GEOTRACES cruises to quantify and age these margin fluxes (Kipp et al., 2018; Kipp et al., 2019; Sanial et al., 2018), which will help constrain the upstream TEI source and downstream scavenging fate of these metals as the margin waters mix into the ACC frontal region.

Models predict hydrothermal vents to be the most significant source of Fe to the South Pacific water column (**Fig. 4a**), given the >4000 km long hydrothermal plume emanating from the Southern East Pacific Rise (SEPR) at 15°S (Resing et al., 2015) and the numerous other South Pacific hydrothermal systems (e.g. Baker et al., 2002). The 15°S SEPR plume was shown on U.S. GEOTRACES GP16 to be a source of metalliferous particles (Fitzsimmons et al., 2017) and dissolved Fe, Mn, Al, and Zn (Resing et al., 2015; Roshan et al., 2016), and it is a sink for particle-reactive trace elements such as Th, Pa, and Pb (Niedermiller and Baskaran, 2019; Pavia et al., 2018). Distal hydrothermal plumes are best traced using the mantle-derived isotope ^3He (Lupton and Craig, 1981), and the presence/absence of linear correlations with ^3He have been used to identify conservative mixing of hydrothermal tracers into the ocean (e.g., Fitzsimmons et al., 2014; Resing et al., 2015). Based on the historical ^3He distribution (**Fig. 5a**) and new data from 10-20°S on U.S. GEOTRACES GP15 (Fitzsimmons and Hatta, unpublished), the northernmost GP17-OCE meridional stations will sample a deep water hydrothermal plume, which could come from the Western Pacific and/or from local vents such as Teahitia and MacDonald Seamounts (German et al., 2020; Stüben et al., 1992), but its spatial extent and metal/^3He ratios have not yet been studied. Additionally, the SEPR plume is known from calculations (Reid, 1997) and models (Faure and Speer, 2012) to include a branch that turns southeastward along 115-135°W (**Fig. 5a**), eventually re-crossing the SEPR at 25-35°S as part of the eastward flowing PDW, which then travels southward along the South American continent to join the deep ACC. GP17-OCE will sample this PDW in high resolution on the margin section, before it rounds Cape Horn to join the ACC in the Drake Passage (see Section C).

Finally, the Pacific sector of the Southern Ocean is an especially important place to study the potential role of margin and cryospheric TEI fluxes from the Antarctic continent, given the rapid melting of the West Antarctic ice sheet over the last two decades (Rignot et al., 2019; Shepherd et al., 2012). The

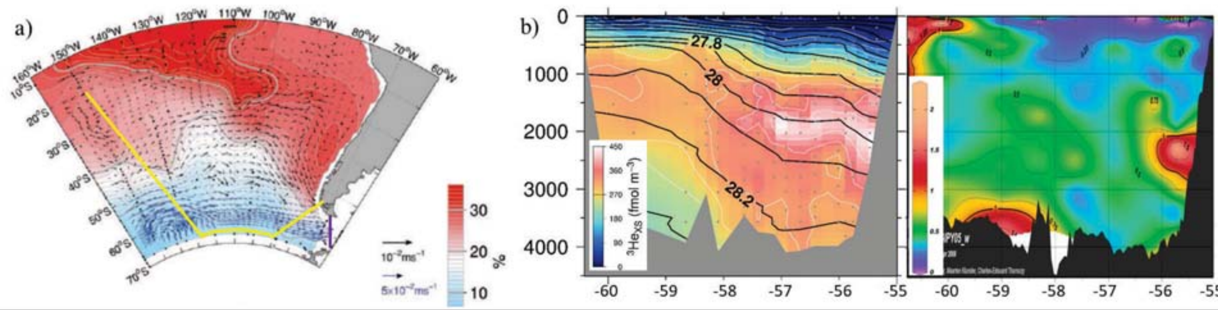

Fig. 5. Observed δ^3He on the PDW γ=27.99 kg/m^3 layer, overlain by modeled velocities (Faure and Speer, 2012). GP17-OCE cruise (yellow) and location of panel B (purple) sections indicated. B) Distributions of $^3He_{xs}$ (Jenkins, in review) and dissolved Fe (Klunder et al., 2014) in the Drake Passage.

Thwaites glacier, which drains into the Amundsen Sea directly south of the GP17-OCE transect, shows the highest risk of irreversible melting, which would trigger sea level rise of >3 m globally (Bamber et al., 2019; Bamber et al., 2009). This meltwater and the continental materials that it resuspends are thought to provide a critical flux of the micronutrient Fe to Antarctica's shelf communities, explaining 59% of the variance in mean chlorophyll *a* concentrations across Antarctica's polynyas (Arrigo et al., 2015). GP17-OCE will enable testing of the northward extent of such cryospheric and sedimentary TEI inputs (Sherrell et al., 2015) by sampling at several stations on the zonal 67°S transect that connect with offshore transects from ice shelf faces in the Amundsen Sea to be sampled by GP17-ANT (**Fig. 2**). The presence of glacial meltwater at 67°S has been shown using sensitive He and Ne isotopes (Hohmann et al., 2002), and we anticipate that other isotope tracers ($\delta^{18}O$, Nd, and/or Ra isotopes) can be used to trace the provenance of any continental material observed. Importantly, we will also assess the extent to which any continental (micro)nutrients are carried northwards to HNLC surface waters within the ACC fronts, where they could support primary production and undergo rapid eastward transport across the Southern Ocean.

B. Internal cycling of TEIs across productivity gradients

GP17-OCE will cross major gradients in (micro)nutrients and productivity within a larger region of low dust flux. This cruise provides a unique opportunity to investigate both the impacts of TEIs on primary production and community composition, as well as the corresponding effects of biological processes on TEI cycling and nutrient signatures. Understanding these feedbacks is critical in this region of major water mass subduction and export.

South Pacific gyre – The meridional section will enable sampling of the ultra-oligotrophic subtropical SPG. The SPG is the largest and most oligotrophic (<0.02 µg/L Chl *a*; **Fig. 6A**) subtropical gyre in the global ocean (Claustre et al., 2008; Longhurst, 2007), but much less is known about the SPG than gyres in the Atlantic or North Pacific (e.g., Boyle et al., 2005; Karl and Church, 2014; Lomas et al., 2013; Moore et al., 2009; Rees et al., 2015). Indeed, past biogeochemical expeditions to the SPG have only measured Fe, among TEIs (Claustre et al., 2008; Fitzsimmons et al., 2016). The SPG serves as the global endmember for oligotrophic ocean conditions, with clear waters that support an extremely deep pycnocline and nutricline, as well as the deepest subsurface chlorophyll maximum layer yet observed (approaching 200m; Claustre et al., 2008; Ras et al., 2008; Twardowski et al., 2007). These conditions make the SPG an ideal location to constrain, for example, TEI impacts of colloidal cycling. In the North Atlantic, a curious absence of colloidal Fe at the deep chlorophyll maximum (DCM; Fitzsimmons et al., 2015a) could have been due either to unique biological uptake in this light-limited depth range (Fitzsimmons et al., 2015b) or to a particle aggregation process that also removed particulate Fe, Th, Ti, and other scavenging-prone TEIs from the water column (Ohnemus and Lam, 2015). These two mechanisms could easily be distinguished on GP17-OCE given the near-absence of dust and the uniquely

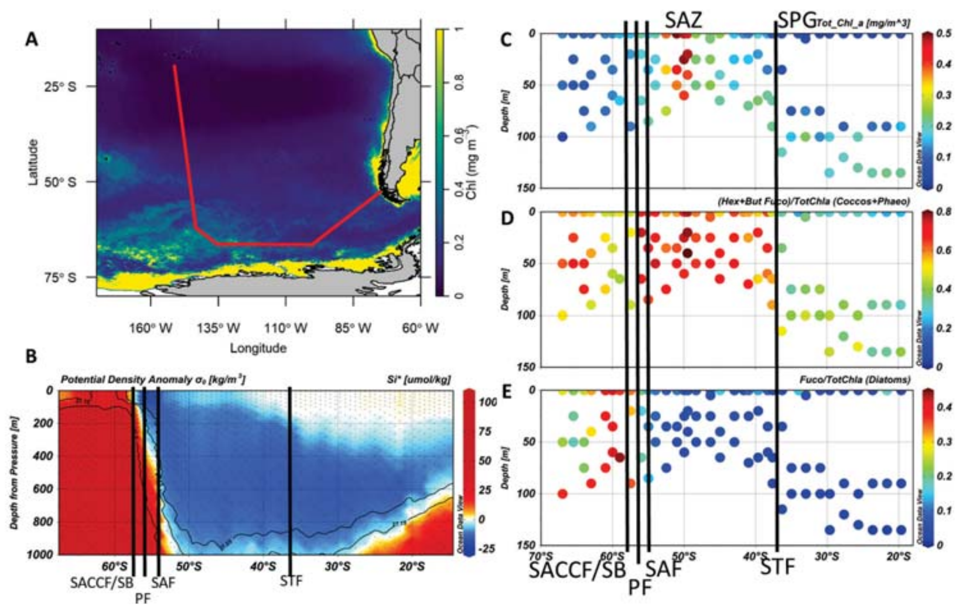

Fig. 6. A) Cruise track overlaid on January Chl *a* climatology (NASA MODIS). B) Si*, potential density anomaly, and photosynthetic pigments (C-E) along 150˚W meridian during 2014 P16S cruise. Major fronts are indicated. Hex+But fuco and fucoxanthin pigments are indicative of haptophytes and diatoms, respectively.

deep DCM, particularly if combined with measurements of biogenic particulate Fe (Twining et al., 2015).

Surface SPG plankton communities are also likely to have unique TEI signatures. Unlike the Atlantic and North Pacific subtropical gyres, SPG surface waters are depleted in both N and Si but also have very low Fe (~0.1nM; Blain et al., 2008; Fitzsimmons et al., 2016; Measures & Landing unpubl.). Trace metal contents of plankton that dominate upper-ocean particles in the SPG likely differ from other gyres due to these extreme nutrient conditions. Indeed, diatoms from the northern edge of SPG have 5-fold higher Fe/C than co-occurring nanoflagellates due to N-limitation, even at low Fe (Twining et al., in prep). Additionally the SPG diazotroph community is predominantly UCYAN A and heterotrophic bacterial groups rather than *Trichodesmium* and *Crocosphaera*-like cyanobacteria most abundant in other gyres (Bonnet et al., 2008; Halm et al., 2011; Shiozaki et al., 2018). These species are largely uncultured, and their TEI contents and stoichiometries are unconstrained. Thus, the SPG presents an opportunity to understand TEI requirements and cycling, particularly by novel diazotrophs, under extremely oligotrophy.

<u>*Frontal zones of the ACC*</u> – The zonal jets of the ACC create strong gradients in macronutrients, TEIs, productivity, and phytoplankton community composition that map onto zones of water mass upwelling and subduction. Thus, biogeochemical processes in the ACC influence nutrient delivery to other regions via SAMW and AAIW (see Section C below; Sarmiento et al., 2004a). Availability of TEIs – notably Fe and potentially Mn – also control productivity in this region, with global C cycle and climate implications. Thus, this is a key region to constrain TEI biogeochemistry, especially since the Pacific sector is less studied than the Atlantic and Indian sectors yet has the most globally relevant water mass implications because of the large volume of intermediate/mode waters formed in this sector.

In the SAZ, Ekman transport carries high-nutrient Antarctic waters northward, causing surface nitrate to decrease from ~20 μM at the PF to limiting levels (<2 μM) at the STF. This allows more abundant phytoplankton in the SAZ compared to the SPG (**Fig. 6C**), but silicate remains low in this zone, with negative Si* across the SAZ (**Fig. 6B**). As a result, the SAZ phytoplankton community is dominated by small, non-silicified cells such as haptophytes (i.e., coccolithophores and *Phaeocystis*) (Balch et al., 2011; Brown and Landry, 2001; Longhurst, 2007; **Fig. 6D**). These groups have different TEI signatures than diatoms abundant further south, including lower Mn, Ni, and Zn quotas (Twining and Baines, 2013), and these small cells drive upper ocean particulate ratios (Barrett et al., 2018). Sampling across this region will enable us to constrain TEI/carbon export ratios as a function of chemical conditions and biological community in the euphotic zone, a well as the imprint by regeneration of these exported elements on the (micro)nutrient stoichiometry of intermediate and deep waters leaving this region.

Solar irradiance also places a first-order control on primary production in the Southern Ocean, resulting in strong seasonality (Uchida et al., 2019), but Pacific sector SAZ waters are also seasonally Fe-limited (Coale et al., 2004; Franck et al., 2000; Hiscock et al., 2003). The spring bloom depletes mixed-layer Fe supplied by winter mixing (e.g., Coale et al., 2005; Measures and Vink, 2001), and by mid-summer (January), SAZ waters are clearly Fe-limited (Coale et al., 2004; Olson et al., 2000), including the coccolithophores abundant in this region (Balch et al., 2016). While Zn appears to be low in the SAZ (Baars and Croot, 2011; Ellwood, 2008), Zn additions have not indicated phytoplankton limitation (Franck et al., 2000). Manganese could potentially limit phytoplankton in Southern Ocean waters, but evidence for this is focused on Atlantic sector (Browning et al., 2014; Middag et al., 2013; Middag et al., 2011a) and Ross Sea (Wu et al., 2019) waters. Manganese measurements from the 2005 P16S cruise show surface Mn < 0.2 nM in the southern SAZ (Landing, unpublished), suggesting this micronutrient could influence productivity in the Pacific sector. The GP17-OCE section will allow us to measure TEI ratios of plankton and particulate matter under simultaneously low Fe and Mn conditions, including in coccolithopores that make important contributions to nutrient export here (Rosengard et al., 2015).

Silicate concentrations increase markedly south of the PF as CDW upwells (**Fig. 6B**), supporting a significant diatom community (**Fig. 6E**) and silica-rich sediments below (Chase et al., 2015). Silicate in the PFZ can be depleted during the summer, limiting diatom growth as the season progresses and allowing *Phaeocystis* and other haptophytes to compete successfully (Franck et al., 2000; Hiscock et al., 2003). Indeed, the competition between diatoms and *Phaeocystis* in Antarctic waters is a key aspect of the ecology of the region (DiTullio and Smith, 1996; Smith and Nelson, 1985), with impacts on nutrient biogeochemistry and C export (Arrigo et al., 2002; Arrigo et al., 1999). *Phaeocystis* and diatoms are assumed to have significantly different TEI ratios (Tagliabue and Arrigo, 2005), and Fe availability is known to affect *Phaeocystis* growth and colony formation (Bender et al., 2018; Garcia et al., 2009), but no measurements of TEIs in *Phaeocystis* have been made. By sampling across gradients in community composition, the GP17-OCE section will allow TEI/C ratios of keystone Antarctic phytoplankton to be constrained, informing models of TEI cycling, export fluxes, and water mass imprinting.

The proposed zonal section along 67˚S also provides opportunities to sample upwelling deep water and determine signatures of phytoplankton growth/conditioning on TEI and macronutrient stoichiometries across a wider distance than the narrow ACC fronts that will be captured on the meridional transect. Not only is this region important for deep sea C efflux to the atmosphere (Takahashi et al., 2002), but the upwelling of deep water macronutrient stoichiometries (particularly the PDW-derived high Si) drives diatom blooms south of the PF that affect patterns in export production and resulting sediment composition (Dutkiewicz et al., 2016). There is also evidence from the GO-SHIP S04P cruises along 67°S of bathymetrically-guided "upwelling hotspots" where pCO_2 exceeds saturation, a clear indicator of upwelling (Takahashi, unpublished). These hotspots are south of the upwelling hotspots identified along the ACC fronts (Tamsitt et al., 2017) but could be driven by similar bathymetric mechanisms. We hope to target one or more of these pCO_2 hotspots with our zonal transect demi stations, in order to study the biogeochemical effects of localized upwelling hotspots, which should bring high macronutrients alongside elevated pCO_2 to the surface ocean, changing the nutrient regime.

C. TEI stoichiometries and cycling in subsurface water masses

As the source region for several globally-relevant intermediate and deep water masses, the Pacific sector of the Southern Ocean is a key location to constrain TEI stoichiometries at their sites of formation ("pre-formed" concentrations) in order to assess regeneration and/or scavenging rates in these water masses downstream (e.g., Middag et al., 2018; Roshan et al., 2018; Weber et al., 2018). The cumulative biological processing in the upper waters of the ACC imparts stoichiometric pre-formed signatures of TEIs and macronutrients that are then carried northward via SAMW, AAIW, and UCDW and impact productivity in lower latitudes (Sarmiento et al., 2004a). For example, increased silicification of Southern Ocean diatoms due to Fe limitation is thought to increase sinking and 'trapping' of Si in the Southern Ocean (e.g., Boyle, 1998; but see also Brzezinski et al., 2003). Vance et al. (2017) posit that relatively high uptake of Zn, like Si, by diatoms in the PFZ similarly traps Zn in the Southern Ocean. The Zn content of these diatoms, as well as Cd and Ni, may be driven by high levels of labile dissolved metals (Vance et al., 2017) or as a result of Fe limitation (Roshan et al., 2018). Coincident measurements of metal speciation with metals in cell biomass could address this question. More recent studies have shown that Zn isotope distributions cannot be reconciled without also invoking reversible scavenging of Zn onto sinking particles (Weber et al., 2018), and scavenging of other TEIs such as Al and Cu are also of interest (Barrett et al., 2018; Middag et al., 2011b; Ohnemus et al., 2019). High-resolution mapping of dissolved and particulate TEI stoichiometries in high-diatom Subpolar Region waters – where external TEI fluxes are minimal – will constrain stoichiometries of metal:nutrient uptake and regeneration, and resolve competing models of TEI cycling. Then, downstream along the GP17-OCE meridional transect, relationships between CFCs, AOU, and TEIs in intermediate/mode waters can allow a differentiation of non-conservative water mass mixing, regeneration, and/or scavenging in these thermocline water masses of global extent. A recent study compiled disparate TEI measurements in this region to suggest that the balance of large regeneration and scavenging fluxes influences observed relationships between Fe and other nutrients, affecting delivery of nutrients via SAMW and AAIW (Tagliabue et al., 2019). By sampling along the path of these water masses, this provocative hypothesis can be directly assessed.

Of particular interest in the HNLC Southern Ocean is how much of the deep Pacific's hydrothermal Fe enrichment, carried in PDW southward, persists by the time PDW upwells to the surface of the Southern Ocean. Some models of Fe biogeochemistry suggest that, downstream of the Drake Passage, upwelled hydrothermal Fe enhances carbon export by ~30% (Resing et al., 2015; Tagliabue et al., 2010), which would position hydrothermal Fe as a critical resource to the Southern Ocean ecosystem. However, these models need ground-truthing by observations of the evolving dFe:^{3}He ratios over distance from their SEPR source. Jenkins (in review) has calculated, based on a global ^{3}He compilation, that the e-folding timescale of ^{3}He upwelling in PDW is 73±15 y, which is within the large window of dissolved Fe deep water residence times of 6-270 y (summarized in Hayes et al., 2018a). This confirms that upwelling of hydrothermal Fe to the Southern Ocean is probable but remains locally contingent on particle concentrations/composition and Fe speciation factors that affect dFe scavenging. On the GP17-OCE margin section, we will sample PDW in high spatial resolution as it leaves the Pacific around Cape Horn to enter the Drake Passage, after which it upwells into the ACC (Faure and Speer, 2012; Fig. 5). Elevated dissolved Fe, Mn, and Al have been observed in Drake Passage PDW but only extending to ~56°S, not ~58°S as ^{3}He (Klunder et al., 2014; Middag et al., 2012a). A comparison of TEI:^{3}He on GP17-OCE's margin section with the Drake Passage ratios will allow an estimate of scavenging rates during transport around Cape Horn. Further comparison to SEPR ratios will allow a calculation of distal scavenging timescales, while acknowledging likely additional hydrothermal TEI inputs along the transport pathway of PDW from the SEPR to the ACC (Baker et al., 2002; Faure and Speer, 2012). Examining TEI behavior in this region is critical to constraining the amount of Fe carried by PDW that may reach the euphotic zone and thus influence the efficiency of the biological pump in the Fe-limited Southern Ocean.

5. Proposed Research

We propose enabling the research outlined above through the provision and support of a 55-day research cruise across South Pacific and Southern Ocean waters. This proposal would fund essential sampling operations, organization, and infrastructure required to host the U.S. GEOTRACES GP17-OCE cruise. The scientific impact of the proposed cruise relies on the individual research projects that will follow, and on the scientific links to the GP17-ANT cruise, but the management infrastructure underpins all of these proposals to come. Thus, the major objectives of this management proposal are to:

1. Plan and coordinate a 55-day research cruise in 2021-2022;
2. Obtain representative samples for a wide variety of TEIs using a conventional CTD/rosette and GEOTRACES Trace Element Sampling System, as well as facilitate sampling for atmospheric aerosols, large volume particles and radionuclides, and upper ocean large volume radionuclides;
3. Acquire 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 for community use; and deliver these data to the GEOTRACES Data Assembly Centre (GDAC) via the U.S. BCO-DMO data center;
4. Ensure that proper QA/QC protocols are followed and reported, as well as fulfilling all GEOTRACES intercalibration protocols;
5. Prepare the final cruise report to be posted on the GDAC web site;
6. Coordinate all cruise communications between GP17-OCE investigators, as well as with leaders of the proposed GP17-ANT cruise;
7. Conduct Broader Impact efforts that will engage the public in oceanographic research using immersive technology.

These objectives mirror those for preceding U.S. GEOTRACES transects, which have resulted in high quality data that is significantly advancing understanding of TEIs in ocean systems and their importance for ocean productivity, health, and reconstruction of past conditions (e.g., Anderson, 2020).

Cruise track and timing

The proposed GP17-OCE transect will include a nearly **meridional** section from 20°S to 67°S, a **zonal** section along 67°S from 135° to 100°W, and a **margin** section from 67°S 100° W to the Chilean margin (**Fig. 2**). We request a 55-day cruise on a Global-class research vessel (R/V *Revelle* or *Thompson*) to occupy 36 stations (types defined below) using our well-established station times and including the deployment of a towed fish for high-resolution surface sampling along the entire 9400 km transect. We request a late-November 2021 – mid-January 2022 cruise window in order to sample the diatom blooms in the Southern ACC near their peak biomass (**Fig. 7a**). We also must sample late enough in summer to take a Global-class research vessel (not icebreaker) to 67°S, which is within ice pack in spring. Thus, we aim to complete our zonal transect in early January, when sea ice climatology indicates ice-free conditions (**Fig. 7b**). A final consideration is allowing for gear and personnel to be shared with a successive companion GP17-ANT cruise into the Amundsen Sea on the R/V *Palmer*. We request that GP17-OCE travels from Tahiti to Punta Arenas to allow for this exchange with GP17-ANT, as well as to allow steaming downwind for the zonal and margin sections to minimize transit times.

The meridional leg would leave from Tahiti at the end of November and re-occupy a crossover with the 2018 U.S. GEOTRACES GP15 station at 20°S 152°W to “anchor” this cruise with the prior one. We will also conduct a GEOTRACES-compliant intercalibration crossover station at 32.5°S 150°W with the 2011 Australia/New Zealand GP13 cruise (e.g. Ellwood et al., 2018; George et al., 2019). The transect will proceed southeastward to 67°S 135°W, striking a balance between resampling the truly-meridional GO-SHIP P16S line along 152°W and arriving at 67°S 135°W at end-December, which is more likely to be ice-free than at 152°W. Additionally, our slightly southeastward heading allows us to sample the ACC fronts at their northernmost location in the Pacific, assuring that we will capture all water masses and gradients described above. It is worth noting that, because the ACC fronts are guided bathymetrically in this region of the Southern Ocean, their latitude is particularly stable at our sampling locations (Kim and Orsi, 2014), raising confidence that we will easily locate them. The zonal leg from 135° to 100°W along

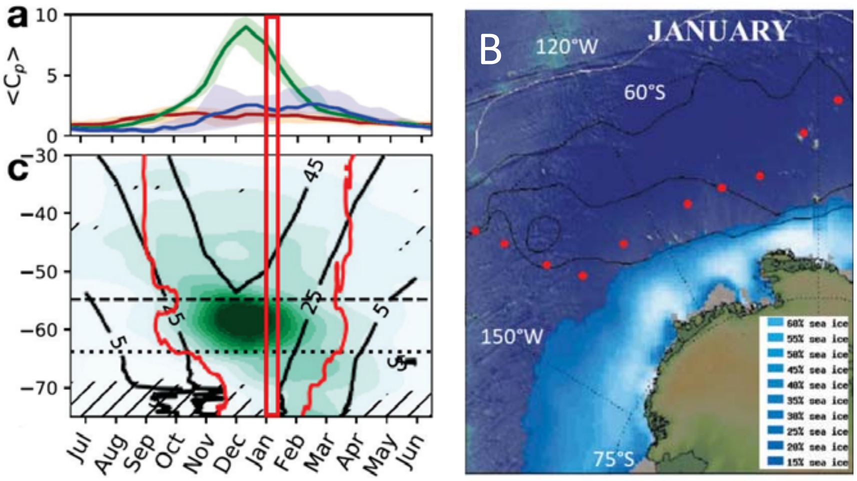

Fig. 7. A,C) Timing of bloom in Pacific sector of Southern Ocean (from Uchida et al., 2019) with sampling period in red. Green shading indicates biomass. B) Ice extent and concentration in January (NSIDC 1979-2007 climatology), with stations shown in red.

67°S will include two crossovers with GP17-ANT that will "anchor" the two GP17 cruises and provide intercalibration stations. Scientifically critical, the GP17-ANT cruise will have several short meridional transects matched with GP17-OCE stations on 67°S, which will allow the quantification of Antarctic margin fluxes to expand farther north across both cruises. Finally, the margin leg of GP17-OCE will sample the southward-flowing PDW then onto the Chilean continental shelf at 52.5°S 75°W. It is important to note that the exact location of all stations, except the three crossovers and terminal stations, will be agreed upon at the pre-cruise PI meeting ~9 months prior to sailing (see Responsibilities below).

Sampling methodology

Three types of stations will be occupied on the GP17-OCE cruise (**Fig. 2**). Full stations will involve sampling the full-depth water column at 24-36 depths using 2-3 casts each of the GEOTRACES trace-metal clean and conventional rosette sampling systems. McLane *in situ* pumps (to be proposed separately) allow large-volume particles and radionuclide TEIs to be sampled at 16 of these depths with 2 casts of 8 pumps each. Based on experience on the 2018 GP15 cruise, a Full station takes 33 hours for 24 depths and 38 hours for 36 depths. Super stations include 6 additional conventional CTD casts, 1 extra trace-metal clean cast, and 1 additional pump cast, and take 48 hours. Demi stations sample the upper 1000 m using only 1 cast each of the trace metal and conventional rosettes, taking a total of 2 hours to complete. In the frontal zones, we will use the ship's ADCP and flow-through sensors such as T, S and fluorescence to help identify the various fronts for station placement.

The water sampling systems and protocols used on all previous U.S. GEOTRACES cruises will be the same on this proposed GP17-OCE section. Another critical carryover will be the use of "Super Techs" to perform all sampling operations, thus ensuring consistency and increasing berthing for other PIs. The overall shipboard methods for this cruise are documented in the Sampling and Sample-Handling Protocols for GEOTRACES Cruises "cookbook" (Cutter et al., 2017), 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, and conventional CTD/rosette sampling. The U.S. GEOTRACES Trace Element Sampling System will be used, and its performance has been thoroughly tested and described (Cutter and Bruland, 2012). Particles from GO-FLO bottles will be collected on 25-mm, 0.2 µm filters following GEOTRACES protocols (Cutter et al., 2017). For TEIs that are not contamination-prone, and to sample water column hydrography, we will use the 36-position, 10-L 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

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performance of GO-FLO bottles (Cutter and Bruland, 2012). 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 the ultra-oligotrophic gyre will be determined under Cutter's supervision.

For near-surface sampling of all dissolved TEIs we will use a trace metal-clean towed "fish" (e.g., Cutter et al., 2017; de Jong et al., 1998) that is deployed ~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 5 L/min into the clean lab van while steaming at 10+ knots, and the water is 0.2-µm capsule-filtered or taken unfiltered. This system will be provided by the Management Team who will use it for all station surface samples because the GEOTRACES rosette cannot be used to collect clean samples in the upper 20 m due to ship contamination (Cutter and Bruland, 2012).

<u>*Analytical Methods*</u>

Hydrography and nutrients. Hydrographic characterization will be conducted by the SIO/Ocean Data Facility (SIO/ODF) team, led by Todd Martz, who will perform measurements 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 Cutter (ODU Budget). Additionally, 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 (2.2-3.2 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 shipboard for dissolved Zn, as it is an excellent indicator of potential sampling contamination (Cutter and Bruland, 2012). For these analyses we will employ the solid phase extraction/fluorescence detection lab-on-valve system described by Grand et al. (2016) with a 0.02 nM Zn detection limit. These measurements will be made at all stations and from all GO-Flo bottles 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 all stations. 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 the Letelier Lab at Oregon State University for HPLC pigment determinations to reveal bulk community composition.

<u>*Management Team roles and responsibilities*</u>

Overall. The four PIs on this proposal compose the Management Team, who will oversee implementation of the U.S. GEOTRACES GP17-OCE cruise, including all aspects of logistics, interaction with the ship operator and agents, communication with the science community, data management, and outreach. Prior to the cruise, we will follow the procedure used on previous U.S. cruises and host a GP17 workshop 6-8 May 2020 at Old Dominion University where interested PIs will learn about the scientific motivations, design, and logistics for the cruise, present their statements of interest, and establish collaborations before their proposal deadline; funding for this workshop will come from the U.S. GEOTRACES Project Office at LDEO, Columbia University. Statements of interest from individual PIs will be posted on the U.S. GEOTRACES web site to facilitate coordination of logistics and assemblage of scientific teams. Participation with this cruise will be open to any U.S. PI who proposes high quality research that supports the GEOTRACES goals. As of 10 February 2020, 66 PIs from 38 institutions had applied to attend this workshop, an excellent reflection of the interest in the cruise from a broad range of the chemical oceanography community. After funding decisions on individual science proposals, we will coordinate a PI pre-cruise meeting in early 2021 to determine shipboard operations including the number, type, and exact locations of the stations to be occupied along the section.

At sea, we will provide 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 and SIO/ODF subcontract in ODU Budget). Water and GO-Flo particle sampling will use the facilities described above. We anticipate that individual PI(s) will provide large-volume *in situ* pumps and the aerosol and precipitation sampling equipment, as on the GA03, GP16, and GN01 cruises. Working with ODF, the management team will also be responsible for monitoring both GO-Flo and Niskin integrity using shipboard hydrographic measurements, as well as dissolved Zn determinations. Post-cruise, the management team will be responsible for ensuring the timely transmission of all data and metadata acquired during the cruise to the U.S. GEOTRACES data archive (BCO-DMO) who, in turn, will be responsible for transferring all such data and metadata to the International GEOTRACES Data Assembly Centre (see Data Management Plan). The management team will also be responsible, together with Todd Martz and SIO/ODF team, for creating a final cruise report and a "hydrographic synthesis" publication 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., 2018). Finally, the management team will host a data synthesis meeting (U.S. GEOTRACES Project Office-funded) ~1.5 years post-cruise to promote collaboration, discussion, and manuscript preparation among participants.

Specific Responsibilities. **Twining** is the lead PI of GP17-OCE and will be the Chief Scientist on the cruise, providing guidance on meeting the overall cruise objectives, as well as those of individual PIs. He will be the point of contact for UNOLS ship schedulers and oversee acquisition of any required international clearances (French Polynesia, Chile). In addition to interfacing with the ship's captain and shoreside operations, he will lead the collection and archiving of GO-FLO particle samples. He has been a PI on the 2010-2011 GA03, 2013 GP16, and GN03 Arctic cruises. **Fitzsimmons** will be a co-leader on the cruise and will oversee all of the trace metal sampling operations and Super Tech activities for the GEOTRACES Sampling System and towed fish operations. She participated on the 2010-2011 GA03 cruises as the first U.S. GEOTRACES Super Tech and also sailed on the 2015 GN01 Arctic cruise; she was a PI on the GN01 and GP15 cruises. **Cutter** will be the other cruise co-leader and will supervise all of the sampling operations and Super Techs for conventional TEIs using the ODF rosette. He has participated as a co-leader on virtually every U.S. GEOTRACES cruise and as Chief Scientist for the 2018 GP15 expedition. As noted above, while he is supplying the U.S. GEOTRACES Sampling System, Fitzsimmons will be in charge of its use. **Wiederwohl** will not participate in the cruise, but will oversee all Broader Impact activities (below).

BROADER IMPACTS

Significance of proposed work

The scientific results that will be generated from this cruise based on the studies of individually-funded PIs will have clear significance to the field of chemical oceanography and biogeochemistry by examining the cycling of trace elements and isotopes. It will extend the GEOTRACES TEI database to a region of the South Pacific and Southern Oceans that are largely under-sampled for TEIs. The Southern Ocean is experiencing changing physics and biogeochemistry that will impact heat, carbon, and nutrient cycles globally (Bronselaer et al., 2020). This cruise will also address: TEI and nutrient cycling in extreme oligotrophic conditions likely to expand with thermal stratification (Polovina et al., 2008; Sarmiento et al., 2004b); transitions between regions of contrasting nutrient limitation; impacts of the biological pump TEI cycling; and long-range impacts of Antarctic ice melting/sediments on productivity.

Virtual Reality exploration of GEOTRACES science and experience

Pedagogical research has shown that student retention of scientific material is enhanced when taught using immersive technological platforms (Huang et al., 2010; Shin, 2002; Won et al., 2019). Thus, we hope to highlight GEOTRACES through Virtual Reality (VR). Working with the Texas A&M University Department of Visualization Learning Interactive Visualization Experience (LIVE) Lab, we will build a 360°/VR experience "Sailing with GEOTRACES" (SWG) for general audiences who don't otherwise have opportunities to sail on research cruises. SWG will allow participants to immerse themselves in life at sea on a GEOTRACES cruise. It will be framed through an isometric view of the research vessel, where multiple "rooms" (i.e., modules) will light up for further exploration. Modules will include visualizations highlighting shipboard experiences, as well as an in-depth look at GEOTRACES science, conducted through a combination of interviews with GP17-OCE scientists, 360° videos, and short games that will allow the participant to become a "GEOTRACES scientist for a day." The goals of the VR experience are twofold: 1) allow the general public to immerse themselves in shipboard scientific life, and 2) educate the public on the overall mission of GEOTRACES and our research focused on this region, as well as the logistics of how this research is accomplished.

Scientifically, individual modules will allow participants to learn the challenges of trace metal-clean sample collection and measurements through, for example, a 360° video tour of the clean lab and a short game where the participant becomes the scientist in charge spotting potential contamination problems in the lab (e.g., rusty hinges, etc.). Also, the GP17-OCE cruise track spanning subtropical and polar waters allows for an "on-deck" component where participants can experience the challenges of working through various weather conditions, including differences in sea-state. A game integrated into this portion of the experience would allow participants to spot things that need securing during high seas.

In order to capture the necessary footage for SWG, a graduate student from the LIVE lab will sail on GP17-OCE to record 360° video footage, conduct interviews of scientists and crew, as well as begin processing the collected footage into the various computer generated imagery (CGI) products. The final SWG product will be produced in the LIVE lab during the following semester. All videos will be captioned for American Disabilities Act accessibility. Once completed, SWG will be housed on the international GEOTRACES outreach website for use by all GEOTRACES affiliated-scientists in their own outreach endeavors, as well as global access for the general public. Included with SWG will be a user's guide with prepared introductory scripts so that non-GP17 GEOTRACES PIs can seamlessly use SWG. We will track SWG usage through Google Analytics (e.g., total viewer counts and location, module popularity, etc.). Additionally, the collection of more specific user demographics will be integrated as part of the VR experience, e.g. a participant will be asked to enter their first name, select age range, gender, and state/country, and now they are an "official Co-Chief Scientist" of the cruise. Furthermore, a trailer for SWG and the associated 360° videos within the experience will be shared via social media where audience statistics will also be collected, e.g. Facebook Insight. We will also boost social media posts to target our intended audiences and help direct web traffic to the GEOTRACES site.

In addition to being publicly available on the GEOTRACES website, each funded GP17-OCE PI can buy an inexpensive VR viewer, e.g. Oculus Go Standalone VR headset, which will allow them to showcase SWG at local K-12 schools, libraries/museums, festivals, and adult service centers in their local areas. This will significantly spread the impact of GEOTRACES across the United States. For this project, Wiederwohl will use SWG in established outreach venues such as a week-long kids Oceanography day camp she created in partnership with the local children's museum in College Station, TX, and several summer camps for high school students held at TAMU each year. Longer term, we hope to expand our global impact by showcasing SWG through the National Academy of Sciences' LabX program (see letter of collaboration from LabX Director Geoffrey Hunt). Wiederwohl will collate the impact of this VR product for presentation at a national oceanographic meeting and a publication.

Training and Mentoring

U.S. GEOTRACES is committed to supporting NSF's goal of providing research opportunities and training for graduate students, postdocs, and early-career scientists. In the 2015-2019 period, at least 18 Ph.D. dissertations included GEOTRACES data. U.S. GEOTRACES hosts promising graduate students in the majority of the Super Tech positions at sea, and we expect at least 3 of these positions on GP17-OCE to be filled by graduate students. This project also includes funding for 3 undergraduates and will provide leadership opportunities to two female Early-Career Scientists.

Results of prior research

B.S. Twining – OCE-1232814: *GEOTRACES Pacific Section: "Characterizing biogenic trace elements across productivity and oxygen gradients in the eastern South Pacific*; $399,960; 10/1/12-9/31/2016. ***Intellectual Merit***: Twining's group participated in the GP16 U.S. GEOTRACES transect and analyzed total and leachable particulate trace elements in samples collected from GO-FLO bottles in the upper 500 m, as well as elemental composition of individual phytoplankton cells. Particulate trace elements from samples below 500m were analyzed by R. Sherrell and J. Fitzsimmons. ***Broader Impacts:*** This award supported a postdoctoral researcher and a female undergraduate student. A 4-part public webinar series on GEOTRACES was produced in collaboration with the COSEE program at the University of Maine, reaching 220 participants in 29 states and 13 countries. ***Publications (9):*** *Boyd et al. (2017); Hawco et al. (2016); Ohnemus et al. (2018); Ohnemus et al. (2017); Ohnemus et al. (2019); Schlitzer et al. (2018); Tagliabue et al. (2019); Twining et al. (2016); Twining et al. (in prep)*. ***Products:*** 7 presentations (including 3 to the general public). ***Data availability:*** All data submitted to BCO-DMO (datasets 648543, 639847, 643270) and included in 2017 Intermediate Data Product.

J.N. Fitzsimmons (Co-PI R. Sherrell) **– OCE-1434493/1713677:** *Collaborative Research: GEOTRACES Arctic section: Dissolved micronutrient trace metal distributions and size partitioning (Fe, Mn, Zn, Cu, Cd, and Ni);* $497,314; 01/15-12/19. ***Intellectual Merit:*** Fitzsimmons' lab analyzed >1000 dissolved and colloidal samples for their metal concentrations in order to determine the sources, sinks, and internal cycling of metals in the Western Arctic. Fitzsimmons led the national and international intercalibration effort for the pan-Arctic GEOTRACES program. ***Broader Impacts:*** This project provided ultrafiltered colloidal samples for three other funded PIs. It also supported a female early career PI, a female graduate student, and four undergraduates, and it resulted in a local public radio show on Arctic climate change**.** ***Publications (8):*** *Hein et al. (2017); Marsay et al. (2018); Kadko et al. (2019); Jensen et al. (2019); Zhang et al.(2019), Jensen et al. (2020), Charette et al. (in review) ; Jensen et al. (fully drafted).* Two more Fitzsimmons group-led manuscripts are planned. ***Products:*** 13 presentations (1 keynote). ***Data Availability:*** All data submitted to BCO-DMO (Project 787555), pending upload.

G.A. Cutter – OCE-1130245: *Collaborative Research: Management and Implementation of US GEOTRACES Eastern Pacific Zonal Transect*; $561,412; 6/2012-5/2015. ***Intellectual Merit:*** This collaborative grant with J. Moffett and C. German was for the second US GEOTRACES cruise, GP16, a zonal transect from coastal Peru and the OMZ waters, to the southern East Pacific Rise, then Tahiti. We were in charge of all contamination-prone sampling operations using the US GEOTRACES Sampling Facility. ***Products:*** Special session at the 2014 AGU Fall Meeting and Data Synthesis Meeting in Nov. 2015. Special Issue of *Marine Chemistry*, 2018. One MS degree, Z. Wambaugh, 2017. 8 Presentations. ***Publications (5):*** *Cutter et al. (2018); German et al. (2020); Ohnemus et al. (2017); Peters et al. (2018); Wambaugh and Cutter (in review)*. ***Broader Impacts****:* Aspects of these GEOTRACES research are incorporated into the graduate and undergraduate courses taught by Cutter, and this cruise trained 3 postdocs and 9 graduate students. ***Data availability****:* all data submitted to BCO-DMO.

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* denotes publications listed in Results of Prior Support

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