

RESEARCH LETTER

10.1002/2014GL059364

Key Points:

- Bottle-scale iron and volcanic ash addition experiments were conducted
- Phytoplankton responded more to the ash than iron in a number of experiments
- The ash is suggested to have relieved phytoplankton manganese (co)limitation

Supporting Information:

- Readme
- Text S1, Tables S1–S3, and Figure S1

Correspondence to:

T. J. Browning,
thomasb@earth.ox.ac.uk

Citation:

Browning, T. J., H. A. Bouman, G. M. Henderson, T. A. Mather, D. M. Pyle, C. Schlosser, E. M. S. Woodward, and C. M. Moore (2014), Strong responses of Southern Ocean phytoplankton communities to volcanic ash, *Geophys. Res. Lett.*, 41, 2851–2857, doi:10.1002/2014GL059364.

Received 21 JAN 2014

Accepted 20 MAR 2014

Accepted article online 21 MAR 2014

Published online 16 APR 2014

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

Strong responses of Southern Ocean phytoplankton communities to volcanic ash

T. J. Browning¹, H. A. Bouman¹, G. M. Henderson¹, T. A. Mather¹, D. M. Pyle¹, C. Schlosser^{2,3}, E. M. S. Woodward⁴, and C. M. Moore²

¹Department of Earth Sciences, University of Oxford, Oxford, UK, ²Ocean and Earth Science, National Oceanography Centre Southampton, University of Southampton, Southampton, UK, ³GEOMAR Helmholtz Centre for Ocean Research Kiel, Kiel, Germany, ⁴Plymouth Marine Laboratory, Plymouth, UK

Abstract Volcanic eruptions have been hypothesized as an iron supply mechanism for phytoplankton blooms; however, little direct evidence of stimulatory responses has been obtained in the field. Here we present the results of twenty-one 1–2 day bottle enrichment experiments from cruises in the South Atlantic and Southern Ocean which conclusively demonstrated a photophysiological and biomass stimulation of phytoplankton communities following supply of basaltic or rhyolitic volcanic ash. Furthermore, experiments in the Southern Ocean demonstrated significant phytoplankton community responses to volcanic ash supply in the absence of responses to addition of dissolved iron alone. At these sites, dissolved manganese concentrations were among the lowest ever measured in seawater, and we therefore suggest that the enhanced response to ash may have been a result of the relief of manganese (co)limitation. Our results imply that volcanic ash deposition events could trigger extensive phytoplankton blooms, potentially capable of significant impacts on regional carbon cycling.

1. Introduction

Phytoplankton growth in the high-nitrate low-chlorophyll (HNLC) regions of the world's oceans is limited by the availability of iron (Fe) [Boyd *et al.*, 2007]. Experiments that have artificially supplied Fe to HNLC waters triggered significant phytoplankton responses, typically including the following: an increase in overall biomass, an increased apparent efficiency of photochemical energy conversion (F_v/F_m), and a shift in the species composition of phytoplankton toward a diatom-dominated community [Boyd *et al.*, 2007]. This biogeochemical response to Fe fertilization has the potential to sequester CO₂ from the atmosphere into the deep ocean. Although the efficiency of such sequestration remains uncertain, recent studies have suggested that significant carbon export is probable under the right conditions [Blain *et al.*, 2007; Smetacek *et al.*, 2012].

The delivery of volcanic ash to Fe-limited waters has been hypothesized as a natural fertilization mechanism, whereby the dissolution of Fe-rich soluble salts on the surface of ash particles (or possibly the ash itself) supplies Fe and potentially relieves limitation [Duggen *et al.*, 2010]. Volcanic ash fertilization of remote Fe-limited waters was proposed to cause the detected atmospheric CO₂ drawdown after the Pinatubo 1991 eruption as a result of postfertilization increases in marine primary productivity [Watson, 1997]. Furthermore, this fertilization mechanism has been hypothesized to drive large-scale perturbations to biogeochemical cycles and climate observed in geological or ice core records [Bay *et al.*, 2004; Cather *et al.*, 2009].

To date, evidence for the volcanic ash fertilization hypothesis has generally relied on either measuring trace metals released from ash [e.g., Olgun *et al.*, 2011, 2013; Duggen *et al.*, 2007; Achterberg *et al.*, 2013], detecting the response of phytoplankton cultured in the laboratory to ash addition [Duggen *et al.*, 2007; Hoffmann *et al.*, 2012], or observing posteruptive phytoplankton blooms using remote sensing [Hamme *et al.*, 2010; Langmann *et al.*, 2010; Achterberg *et al.*, 2013]. Recent results from a bottle-enrichment experiment in the North Atlantic have demonstrated the fertilization potential of Icelandic volcanic ash in a region not normally considered to be a classic HNLC system [Achterberg *et al.*, 2013], while a positive phytoplankton community response to ash addition after a four-day time lag has recently been reported for the HNLC North Pacific [Mélánçon *et al.*, 2014]. Until now, however, the response of phytoplankton to ash fertilization in the Southern Ocean, the most biogeochemically significant HNLC system [Sigman *et al.*, 2010], has remained untested. Here we present the results from a suite of Fe and volcanic ash addition

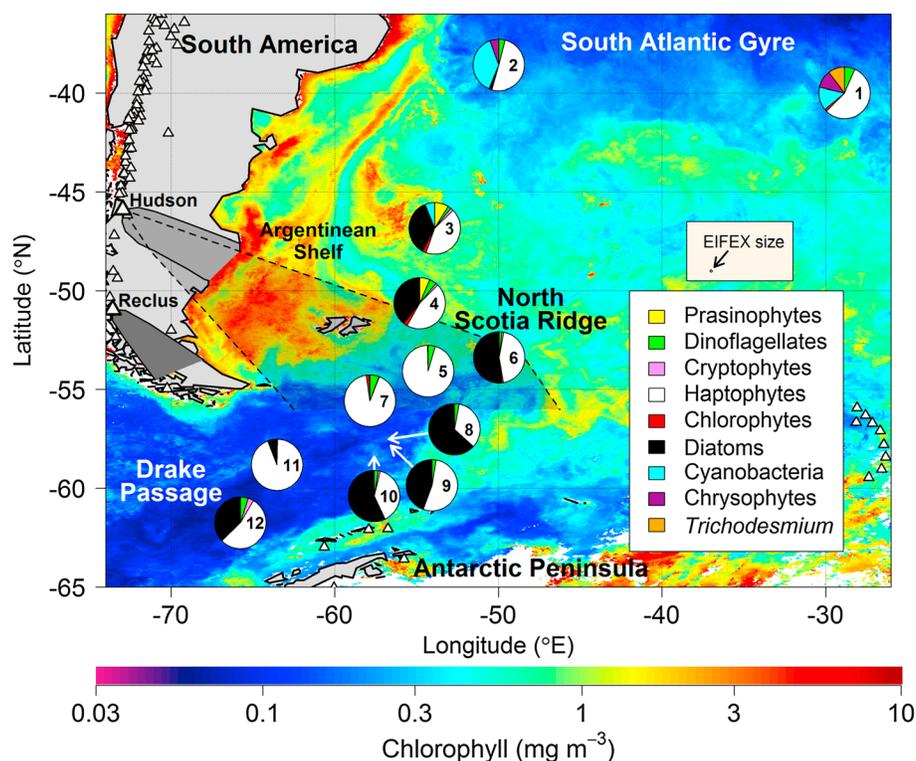


Figure 1. Phytoplankton types and chlorophyll concentrations at experimental sites. Background image shows a January-to-March 2012 satellite composite of chlorophyll concentrations from Moderate Resolution Imaging Spectroradiometer (<http://oceancolor.gsfc.nasa.gov/>). Overlain pie charts represent the dominant phytoplankton types present in waters at each experimental site. Experiment numbers are labeled. Triangles show the locations of volcanoes thought to have been active in the last 10,000 years (Global Volcanism Program, <http://www.volcano.si.edu/index.cfm>). To illustrate the potential scale of natural ash additions in this region, volcanic ash deposition from two Quaternary volcanic eruptions are shown (grey-shaded regions enclosed in solid lines): >10 mm isopach (ash thickness) for the Hudson 1991 eruption [Scasso *et al.*, 1994] (light grey); and >30 mm isopach for the ~14.8 cal ka B.P. Reclus R1 eruption [Stern, 2008; Fontijn *et al.*, 2014] (dark grey). Note that, although likely extending into open ocean waters, no Reclus isopachs (dark grey) have been mapped further south than the region highlighted. The shaded region bounded by the dashed line represents the 15 August 1991 Hudson ash cloud extent from the Total Ozone Mapping Spectrometer aerosol index (<http://ozoneaq.gsfc.nasa.gov/index.md>). For scale, the size of the 167 km² Fe-fertilized patch for the European Iron Fertilization Experiment (EIFEX) is shown by a circle in the inset box.

experiments conducted across a range of oceanic regimes (subtropical gyre, productive shelf, and HNLC waters; see Figure 1). These provide clear evidence for the potential for volcanic ash deposition to stimulate phytoplankton growth in the Southern Ocean.

2. Methods

Incubation experiments were carried out on consecutive cruises in the South Atlantic and Southern Ocean from January to March 2012 (Figure 1 and Tables S1 and S2 in the supporting information). For full method details see supporting information. Briefly, incubation bottles were filled with surface seawater and spiked with either a FeCl₃ solution or volcanic ash. Both basaltic (Etna, Sicily 2002 eruption) and rhyolitic (Chaitén, Chile 2008 eruption—sample of Watt *et al.* [2009]) ash was used, with masses of ash added reflecting realistic seawater loading and dilution within a 50 m surface mixed layer (see supporting information). Fertilized bottles were incubated in an environment simulating the upper ocean for 24 h (48 h for experiment 12). Subsequently, bottles were subsampled for phytoplankton photophysiology and chlorophyll concentrations using fluorescence techniques (Kolber *et al.* [1998] and Holm-Hansen *et al.* [1965], respectively). Active chlorophyll fluorescence measurements using Fast Repetition Rate fluorometry were used to calculate the apparent photochemical efficiency of photosystem II (F_v/F_m), providing a sensitive and rapidly responding indication of relief from Fe limitation [Behrenfeld and Milligan, 2013].

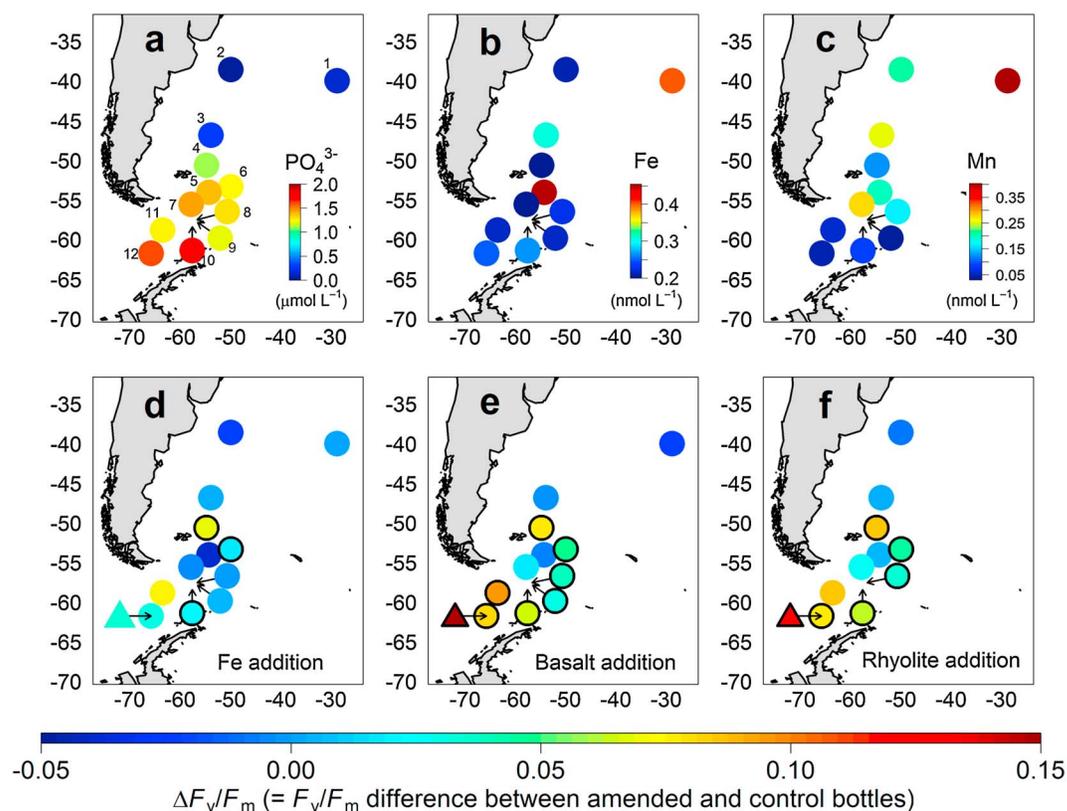


Figure 2. Seawater nutrient concentrations and the response of phytoplankton to iron and ash additions. Dots represent the locations of experiments, with colors representing (a–c) the nutrient concentration or (d–e) the level of phytoplankton response. Experiment numbers are labeled in Figure 2a. Nitrate concentrations showed a strong correlation with phosphate (Figure 2a) ($R^2 = 0.97$; $p < 0.001$). For Figures 2d and 2e: $\Delta F_v/F_m = F_v/F_m$ of waters amended with iron spike (Figure 2d) or ash (Figures 2e and 2f) $- F_v/F_m$ control bottles [Ryan-Keogh et al., 2013]; circular symbols represent the response after 24 h incubation, triangles after 48 h incubation; black outlines around symbols indicate a statistically significant response from amended bottles over control bottles (t test $p < 0.05$). Arrows point to the sites of experiments 8–10 and 12 (labeled in Figure 2a).

Measurements on untreated surface-waters characterized the initial nutrient regime and phytoplankton community present. Trace metal micronutrient concentrations were determined by inductively coupled plasma-mass spectrometry following the method of Milne et al. [2010], while macronutrient concentrations were determined using a segmented flow colorimetric autoanalyzer [Woodward and Rees, 2001]. Phytoplankton community structure was determined by analyzing the accessory pigment composition using high-performance liquid chromatography [Gibb et al., 2000], combined with the CHEMTAX program for assessing the contribution of phytoplankton types to total chlorophyll biomass [Mackey et al., 1996]. Short-duration (2 h) leaching experiments were also conducted using Milli-Q deionized water to characterize the release of trace metals from the two types of ash used. Metals released using such experiments likely represent an upper bound of solubility in seawater due to the more acidic nature of Milli-Q over seawater.

3. Results and Discussion

Initial phytoplankton biomass, community structure, and macronutrient concentrations showed expected patterns for the oceanic provinces encountered. Chlorophyll concentrations increased from the South Atlantic Gyre to the Argentinean Shelf and North Scotia Ridge before declining significantly in the Drake Passage (Figure 1 and Table S1 in the supporting information). Phytoplankton community structure showed a general north-to-south shift from haptophyte-cyanobacteria-dominated communities in gyre waters to haptophyte-diatom-dominated communities in the Southern Ocean (Figure 1). Nitrate and phosphate increased from low, depleted values in gyre waters to much increased values in the Drake Passage (Figure 2a), while silicate increased south of the polar front (Table S1 in the supporting information). Concentrations of the trace metal

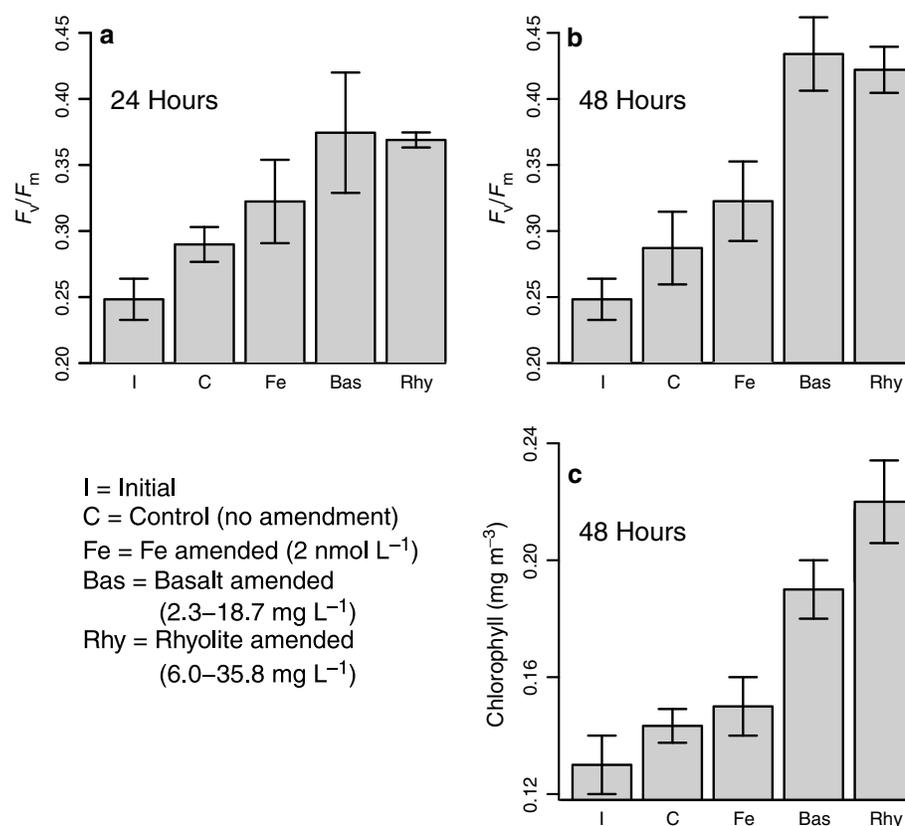


Figure 3. Phytoplankton response to ash addition in Drake Passage (experiment 12): (a and b) the initial photophysiological status and response after 24 and 48 h, respectively; (c) the initial chlorophyll concentration and response after 48 h.

micronutrients Fe and manganese (Mn) generally demonstrated a north-to-south reduction (Figures 2b and 2c and Table S1 in the supporting information). Concentrations of Mn in the surface waters of Drake Passage reached as low as $0.034 \text{ nmol L}^{-1}$, representing some of the lowest values ever measured in seawater, comparable with previous minimal Southern Ocean values ($\sim 0.04 \text{ nmol L}^{-1}$) [Middag *et al.*, 2011, 2012, 2013]. Other trace metals of biological importance (Zn, Cu, Ni, and Cd) were at concentrations expected to be in excess of phytoplankton requirements [Bruland *et al.*, 1991] (see Text S1 and Table S1 in the supporting information).

Of the 23 sets of triplicate bottles amended with ash, 18 sets produced statistically significant (t test $p < 0.05$) increases in F_v/F_m relative to control (nonamended) bottles. For the remaining five experiments, located in macronutrient-depleted South Atlantic waters (experiments 1 and 2) and three sites around the Falkland Islands (experiments 3, 5, and 7), there was no response to either Fe or ash addition. In marked contrast to previous experiments performed in the North Atlantic [Achterberg *et al.*, 2013], phytoplankton responses to ash addition were always greater than those in Fe-spiked bottles (Figures 2d–2f and Table S2 in the supporting information). Particularly enhanced responses from phytoplankton amended with ash, relative to those amended only with Fe, were found in the vicinity of Drake Passage (Figures 2d–2f and also see Figure 3)—a region widely assumed to be severely Fe limited [Martin *et al.*, 1990; Hopkinson *et al.*, 2007]—and containing some of the lowest chlorophyll concentrations in the Southern Ocean ($< 0.1 \text{ mg m}^{-3}$).

In order to limit the potential for confounding taxonomic changes to influence the interpretation of physiological (F_v/F_m) responses [Suggett *et al.*, 2009], experimental durations were typically kept short enough (24 h) to prevent significant increases in biomass (Table S2 in the supporting information). However, within the single experiment run over a longer time scale in Drake Passage, both F_v/F_m and chlorophyll concentrations in the ash-amended bottles increased significantly above that of the control and Fe-amended bottles (Figure 3). Significantly enhanced physiological and growth responses were thus observed for ash-amended phytoplankton.

There are a number of possible explanations for why the volcanic ash additions stimulated phytoplankton more than Fe-only additions. A difference in total Fe supply between treatments appears to be unlikely for several reasons: (i) While some of the ash loadings were potentially capable of releasing more Fe than the 2 nmol L^{-1} Fe-spike (Figure S1 in the supporting information), this level would typically already be expected to be capable of relieving phytoplankton Fe stress. Overall biological demand for Fe might be expected to be relatively lower in the Drake Passage, where the lowest phytoplankton concentrations were observed. Drake Passage sites nonetheless responded to ash addition but not to the Fe-only spike, while other sites responded significantly to the same Fe-only amendment. (ii) Comparing the results of the laboratory ash leaching experiments for the two ash types suggested that the rhyolitic ash likely released significantly less Fe than the artificial Fe spike (see Text S1, Table S3, and Figure S1 in the supporting information). (iii) Despite differential Fe release per unit mass of ash (around 100% for a given ash type in leaching experiments, likely due to a heterogeneous distribution of soluble trace metals in/on the ash; see Table S3 in the supporting information), alongside significant variability in total loadings (Figure S1), similar phytoplankton responses were observed across bottles. For example, within experiment 12 the mass of ash added to individual bottles varied by an order of magnitude, yet the relative standard deviation of responses between bottles was less than 20%. Overall, the total Fe added during amendment (ash or spike) thus appeared to be an unlikely determining factor in phytoplankton responses.

Addition of acidified FeCl_3 will increase oxidized Fe (III) to concentrations which would promote rapid Fe precipitation unless immediately complexed by biologically produced organic ligands [Schlosser *et al.*, 2011]. In contrast, ash may release significant reduced Fe (II) (e.g., from FeCl_2 or FeF_2 salts) [Duggen *et al.*, 2010], which could persist in cold Southern Ocean waters for several hours prior to oxidation [Croot and Laan, 2002]. Furthermore, the dissolution or release kinetics of Fe from ash particles could result in a more continuous supply of Fe (II) for a limited period (~up to 1 h) [Olgun *et al.*, 2011]. As the Drake Passage waters were the coldest encountered (~ 2°C for surface waters) and might be expected to be characterized by low organic ligand concentrations due to low overall biomass [Boye *et al.*, 2001], semicontinuous Fe (II) delivery from ash resulting in a greater effective bioavailability to the resident phytoplankton population could be considered possible. However, the ubiquity of the enhanced ash response across >3 orders of magnitude in ash loading (Figure S1 in the supporting information) argues against such an explanation. We therefore consider (co) limitation of phytoplankton by another essential trace metal nutrient to be the most likely explanation for the marked enhancement in phytoplankton response to ash addition.

Colimitation of phytoplankton by Mn in Drake Passage was suggested as early as 1990 by Martin and coworkers [Martin *et al.*, 1990], although no subsequent direct evidence has been found. Our Mn data demonstrated surface concentrations in this region to be amongst the lowest ever measured in seawater (Figure 2c) [Middag *et al.*, 2011, 2012, 2013], with dissolved Mn:Fe ratios as low as 0.16 being well below typical phytoplankton cellular Mn:Fe ratios [Moore *et al.*, 2013]. Mn is required for a variety of biological processes, including as an essential and nonsubstitutable cofactor in the oxygen-evolving complex of photosystem II within the light reactions of photosynthesis [Morel *et al.*, 2003]. Moreover, Mn requirements and Mn:Fe ratios may be particularly enhanced under Fe limitation [Middag *et al.*, 2013; Peers and Price, 2004], with relief of Fe-Mn colimitation resulting in enhanced growth and F_v/F_m in laboratory phytoplankton cultures [Peers and Price, 2004]. The basaltic ash released far more Fe than the rhyolitic ash, while, in contrast, both ashes released similar amounts of Mn (Table S3 in the supporting information). Consequently, we suggest that the observed similarity in enhanced phytoplankton responses to both ash types indicates the potential significance of relief of Mn (co)limitation.

The clear phytoplankton responses we observed to ash addition have important implications for Southern Ocean biogeochemistry. Enhanced phytoplankton growth following ash addition would be expected to increase the flux of CO_2 between the atmosphere and the surface ocean organic carbon pool, and potentially drive a shift to larger, more rapidly sinking taxa [Boyd *et al.*, 2007; Smetacek *et al.*, 2012; Moore *et al.*, 2007] enhancing carbon export to the deep ocean where it can remain sequestered for centuries or longer [Sigman *et al.*, 2010; Williams and Follows, 2011]. In comparison to the recent European Iron Fertilization Experiment (EIFEX), where a few thousand tons of carbon was estimated to be sequestered from a fertilization area of only 167 km^2 [Smetacek *et al.*, 2012], the much larger aerial extent (Figure 1) and enhanced stimulatory response (Figures 2d–2f and 3) which would likely accompany a major ash deposition event could thus potentially result in regionally or even globally significant carbon sequestration [Watson, 1997].

Although requiring further verification, both our suggested explanations for the significantly enhanced stimulatory response to ash over that of Fe alone (namely greater bioavailability of ash-released Fe (II) and/or the release of (co)limiting Mn) would also have important biogeochemical implications. Specifically, we suggest that significant changes in the biogeochemistry of Drake Passage, which currently represents some of the lowest-chlorophyll high-nitrate waters found anywhere in the surface ocean, may not simply depend on overall increases in Fe supply. Rather, the form of external Fe delivery may be significant and/or an accompanying Mn input might be required to drive significantly enhanced productivity and carbon export. Thus, for example, as sedimentary Fe sources might be expected to be accompanied by Mn [e.g., *Measures et al.*, 2013; *Hatta et al.*, 2013], the combined input of both Fe and Mn may be partially responsible for near coastal phytoplankton responses observed in Drake Passage [e.g., *Hopkinson et al.*, 2007].

Irrespective of the exact cause for our observations, erupted volcanic material appears to be an effective fertilizer for this region. The Drake Passage and the western margin of the South Atlantic are areas of the Southern Ocean that are highly prone to tephra deposition from explosive volcanic eruptions [*Olgun et al.*, 2011; *Fontijn et al.*, 2014]. Large late Quaternary eruptions from volcanoes of both the Andean Austral and Southern Volcanic Zones have deposited considerable volumes of andesitic to rhyolitic tephra across the Drake Passage and into Antarctica [*Stern*, 2008; *Narcisi et al.*, 2012]; while several eruptions per century from Patagonian volcanoes have delivered tephra to the western reaches of the South Atlantic [*Scasso et al.*, 1994]. Rates and sizes of eruptions may well have varied significantly between peak-glacial and postglacial times, depending on the extent of ice cover across Patagonia [*Watt et al.*, 2013]. Consequently, there is the potential for long time scale variability in the extent of ash-driven fertilization and carbon export from these waters.

Acknowledgments

We thank the officers, crew, technicians, and scientists for their help on the UK-GEOTRACES JC068 and DIMES JC069 cruises. Particular thanks go to Andrew J. Watson and Alberto C. Naveira Garabato for allowing us to participate on the DIMES cruise. Thanks to Sebastian Watt, Felicity, and William Mather for collecting the ash samples. Thanks to Yu-Te Hsieh and Philip Holdship for assistance with leaching experiments. Nazli Olgun and an anonymous reviewer are thanked for providing useful comments on the manuscript. This work was funded by the UK-GEOTRACES NERC Consortium grant (NE/H006095/1, which included a studentship to T.J.B.) and NCEO/COMET (T.A.M. and D.M.P.).

The Editor thanks Nazli Olgun and an anonymous reviewer for their assistance in evaluating this paper.

References

- Achterberg, E. P., et al. (2013), Natural iron fertilization by the Eyjafjallajökull volcanic eruption, *Geophys. Res. Lett.*, *40*, 921–926, doi:10.1002/grl.50221.
- Bay, R. C., N. Bramall, and P. B. Price (2004), Bipolar correlation of volcanism with millennial climate change, *Proc. Natl. Acad. Sci. U. S. A.*, *101*, 6341–6345.
- Behrenfeld, M. J., and A. J. Milligan (2013), Photophysiological expressions of iron stress in phytoplankton, *Annu. Rev. Mar. Sci.*, *5*, 217–246.
- Blain, S., et al. (2007), Effect of natural iron fertilization on carbon sequestration in the Southern Ocean, *Nature*, *446*, 1070–1074.
- Boyd, P. W., et al. (2007), Mesoscale iron enrichment experiments 1993–2005: Synthesis and future directions, *Science*, *315*, 612–617.
- Boye, M., C. M. G. Van den Berg, J. T. M. De Jong, H. Leach, P. Croot, and H. J. de Baar (2001), Organic complexation of iron in the Southern Ocean, *Deep Sea Res., Part I*, *48*, 1477–1497.
- Bruland, K. W., J. R. Donat, and D. A. Hutchins (1991), Interactive influences of bioactive trace-metals on biological production in oceanic waters, *Limnol. Oceanogr.*, *36*, 1555–1577.
- Cather, S. M., N. W. Dunbar, F. W. McDowell, W. C. McIntosh, and P. A. Scholle (2009), Climate forcing by iron fertilization from repeated ignimbrite eruptions: The icehouse-silicic large igneous province (SLIP) hypothesis, *Geosphere*, *5*, 315–324.
- Croot, P. L., and P. Laan (2002), Continuous shipboard determination of Fe(II) in polar waters using flow injection analysis with chemiluminescence detection, *Anal. Chim. Acta*, *466*, 261–273.
- Duggen, S., P. Croot, U. Schacht, and L. Hoffmann (2007), Subduction zone volcanic ash can fertilize the surface ocean and stimulate phytoplankton growth: Evidence from biogeochemical experiments and satellite data, *Geophys. Res. Lett.*, *34*, L01612, doi:10.1029/2006GL027522.
- Duggen, S., N. Olgun, P. Croot, L. Hoffmann, H. Dietze, P. Delmelle, and C. Teschner (2010), The role of airborne volcanic ash for the surface ocean biogeochemical iron-cycle: A review, *Biogeosciences*, *7*, 827–844.
- Fontijn, K., S. M. Lachowycz, H. Rawson, D. M. Pyle, T. A. Mather, J. A. Naranjo, and H. Moreno-Roa (2014), Late Quaternary tephrostratigraphy of southern Chile and Argentina, *Quat. Sci. Rev.*, *89*, 70–84.
- Gibb, S. W., R. G. Barlow, D. G. Cummings, N. W. Rees, C. C. Trees, P. Holligan, and D. Suggett (2000), Surface phytoplankton pigment distributions in the Atlantic Ocean: An assessment of basin scale variability between 50 degrees N and 50 degrees S, *Prog. Oceanogr.*, *45*, 339–368.
- Hamme, R. C., et al. (2010), Volcanic ash fuels anomalous plankton bloom in subarctic northeast Pacific, *Geophys. Res. Lett.*, *37*, L19604, doi:10.1029/2010GL044629.
- Hatta, M., K. E. Selph, M. Zhou, and W. T. Hiscock (2013), Iron fluxes from the shelf regions near the South Shetland Islands in the Drake Passage during the austral-winter 2006, *Deep Sea Res., Part II*, *90*, 89–101.
- Hoffmann, L. J., E. Breitbarth, M. V. Ardelan, S. Duggen, N. Olgun, M. Hassellöv, and S. Å. Wängberg (2012), Influence of trace metal release from volcanic ash on growth of *Thalassiosira pseudonana* and *Emiliania huxleyi*, *Mar. Chem.*, *132*, 28–33.
- Holm-Hansen, O., C. J. Lorenzen, R. W. Holmes, and J. D. H. Strickland (1965), Fluorometric determination of chlorophyll, *J. Cons. Perm. Int. Explor. Mer.*, *30*, 3–15.
- Hopkinson, B. M., B. M. Hopkinson, B. Greg Mitchell, R. A. Reynolds, H. Wang, K. E. Selph, C. I. Measures, C. D. Hewes, O. Holm-Hansen, and K. A. Barbeau (2007), Iron limitation across chlorophyll gradients in the southern Drake Passage: Phytoplankton responses to iron addition and photosynthetic indicators of iron stress, *Limnol. Oceanogr.*, *52*, 2540–2554.
- Kolber, Z. S., O. Prasil, and P. G. Falkowski (1998), Measurements of variable chlorophyll fluorescence using fast repetition rate techniques: Defining methodology and experimental protocols, *Biochim. Biophys. Acta, Bioenerg.*, *1367*, 88–106.
- Langmann, B., K. Zakšek, M. Hort, and S. Duggen (2010), Volcanic ash as fertiliser for the surface ocean, *Atmos. Chem. Phys.*, *10*(8), 3891–3899.
- Mackey, M. D., D. J. Mackey, H. W. Higgins, and S. W. Wright (1996), CHEMTAX—A program for estimating class abundances from chemical markers: Application to HPLC measurements of phytoplankton, *Mar. Ecol. Prog. Ser.*, *144*, 265–283.
- Martin, J. H., R. M. Gordon, and S. E. Fitzwater (1990), Iron in Antarctic waters, *Nature*, *345*, 156–158.

- Measures, C. I., M. T. Brown, K. E. Selph, A. Apprill, M. Zhou, M. Hatta, and W. T. Hiscock (2013), The influence of shelf processes in delivering dissolved iron to the HNLC waters of the Drake Passage, Antarctica, *Deep Sea Res., Part II*, *90*, 77–88.
- Mélançon, J., et al. (2014), Early response of the northeast subarctic Pacific plankton assemblage to volcanic ash fertilization, *Limnol. Oceanogr.*, *59*(1), 55–67.
- Middag, R., H. J. W. De Baar, P. Laan, P. H. Cai, and J. C. Van Ooijen (2011), Dissolved manganese in the Atlantic sector of the Southern Ocean, *Deep Sea Res., Part II*, *58*(25), 2661–2677.
- Middag, R., H. J. W. Baar, P. Laan, and O. Huhn (2012), The effects of continental margins and water mass circulation on the distribution of dissolved aluminum and manganese in Drake Passage, *J. Geophys. Res.*, *117*, C01019, doi:10.1029/2011JC007434.
- Middag, R., H. J. de Baar, M. B. Klunder, and P. Laan (2013), Fluxes of dissolved aluminum and manganese to the Weddell Sea and indications for manganese co-limitation, *Limnol. Oceanogr.*, *58*(1), 287–300.
- Milne, A., W. Landing, M. Bizimis, and P. Morton (2010), Determination of Mn, Fe, Co, Ni, Cu, Zn, Cd and Pb in seawater using high resolution magnetic sector inductively coupled mass spectrometry (HR-ICP-MS), *Anal. Chim. Acta*, *665*, 200–207.
- Moore, C. M., S. Seeyave, A. E. Hickman, J. T. Allen, M. I. Lucas, H. Planquette, R. T. Pollard, and A. J. Poulton (2007), Iron-light interactions during the CROZet natural iron bloom and EXPORT experiment (CROZEX) I: Phytoplankton growth and photophysiology, *Deep Sea Res., Part II*, *54*, 2045–2065.
- Moore, C. M., et al. (2013), Processes and patterns of oceanic nutrient limitation, *Nat. Geosci.*, *6*(9), 701–710.
- Morel, F. M. M., A. J. Milligan, and M. A. Saito (2003), Marine bioinorganic chemistry: The role of trace metals in the ocean cycles of major nutrients, in *Treatise on Geochemistry*, vol. 6, edited by K. K. Turekian and H. D. Holland, pp. 113–143, Elsevier, Cambridge, U. K.
- Narcisi, B., J. R. Petit, B. Delmonte, C. Scarchilli, and B. Stenni (2012), A 16,000-yr tephra framework for the Antarctic ice sheet: A contribution from the new Tabs Dome core, *Quat. Sci. Rev.*, *49*, 52–63.
- Olgun, N., S. Duggen, P. L. Croot, P. Delmelle, H. Dietze, U. Schacht, N. Óskarsson, C. Siebe, A. Auer, and D. Garbe-Schönberg (2011), Surface ocean iron fertilization: The role of airborne volcanic ash from subduction zone and hot spot volcanoes and related iron fluxes into the Pacific Ocean, *Global Biogeochem. Cycles*, *25*, GB4001, doi:10.1029/2009GB003761.
- Olgun, N., S. Duggen, D. Andronico, S. Kutterolf, P. Croot, S. Giammanco, P. Censi, and L. Randazzo (2013), Possible impacts of volcanic ash emissions of Mount Etna on the primary productivity in the oligotrophic Mediterranean Sea: Results from nutrient-release experiments in seawater, *Mar. Chem.*, *152*, 32–42.
- Peers, G., and N. M. Price (2004), A role for manganese in superoxide dismutases and growth of iron-deficient diatoms, *Limnol. Oceanogr.*, *49*, 1774–1783.
- Ryan-Keogh, T. J., A. I. Macey, M. C. Nielsdóttir, M. I. Lucas, S. S. Steigenberger, M. C. Stinchcombe, E. P. Achterberg, T. S. Bibby, and C. Mark Moore (2013), Spatial and temporal development of phytoplankton iron stress in relation to bloom dynamics in the high-latitude North Atlantic Ocean, *Limnol. Oceanogr.*, *58*(2), 533–545.
- Scasso, R. A., H. Corbella, and P. Tiberi (1994), Sedimentological analysis of the tephra from the 12–15 August 1991 eruption of Hudson Volcano, *Bull. Volcanol.*, *56*, 121–132.
- Schlosser, C., C. L. De La Rocha, and P. L. Croot (2011), Effects of iron surface adsorption and sample handling on iron solubility measurements, *Mar. Chem.*, *127*, 48–55.
- Sigman, D. M., M. P. Hain, and G. H. Haug (2010), The polar ocean and glacial cycles in atmospheric CO₂ concentration, *Nature*, *466*(7302), 47–55.
- Smetacek, V., et al. (2012), Deep carbon export from a Southern Ocean iron-fertilized diatom bloom, *Nature*, *487*, 313–319.
- Stern, C. R. (2008), Holocene tephrochronology record of large explosive eruptions in the southernmost Patagonian Andes, *Bull. Volcanol.*, *70*, 435–454.
- Suggett, D. J., C. M. Moore, A. E. Hickman, and R. J. Geider (2009), Interpretation of fast repetition rate (FRR) fluorescence: Signatures of phytoplankton community structure versus physiological state, *Mar. Ecol. Prog. Ser.*, *376*, 1–19.
- Watson, A. J. (1997), Volcanic iron, CO₂, ocean productivity and climate, *Nature*, *385*, 587–588.
- Watt, S. F. L., D. M. Pyle, T. A. Mather, R. S. Martin, and N. E. Matthews (2009), Fallout and distribution of volcanic ash over Argentina following the May 2008 explosive eruption of Chaiten, Chile, *J. Geophys. Res.*, *114*, B04207, doi:10.1029/2008JB006219.
- Watt, S. F. L., D. M. Pyle, and T. A. Mather (2013), The volcanic response to deglaciation: Evidence from glaciated arcs and a reassessment of global eruption records, *Earth Sci. Rev.*, *122*, 77–102.
- Williams, R. G., and M. J. Follows (2011), *Ocean Dynamics and the Carbon Cycle*, Cambridge Univ. Press, Cambridge, U. K.
- Woodward, E. M. S., and A. P. Rees (2001), Nutrient distributions in an anticyclonic eddy in the North East Atlantic Ocean, with reference to nanomolar ammonium concentrations, *Deep Sea Res., Part II*, *48*, 775–794.