We would again like to thank Damien Cardinal and Patricia Grasse for their thorough reviews of our manuscript and their helpful comments. Here we present a point by point reply to each review separately, alongside the changes made to the manuscript. Note that the italicized text represents the comments made by the reviewers and the non-italicized/bold text is our response. Also, any changes made to the manuscript cite the page and line numbers from the modified "track changes" manuscript.

Cardinal Review

P4 L2 vs. Table 1: in the text neb flow rate is 100 uL/min while it is 60 uL/min in Table 1. Homogenise. **This has been changed in Table 1.**

- Fig. 4 and in the text associated. 1) In this figure, the authors compare their GEOVIDE data with the two previous studies in the North Atlantic of Brzezinski & Jones (2015) and de Souza et al. (2012). Since Brzezinski & Jones chose to correct the offset between their data and the ones of de Souza et al. by +- 0.11 pmil, I suggest the authors here clearly mention that they always use the non-corrected data (which I believe is the right way to proceed) to avoid confusion with corrected data discussed in Brzezinski & Jones. 2) Important. Provide error bars of the three slopes and intercepts. Variability of GEOVIDE dataset seems higher. This should be checked and discussed. It is particularly needed given the offset found between the three data set that remains unsolved. **We have taken into consideration the recommendations made by the reviewer and have made the following changes:**

(1) The following text was modified on Page 7 Lines 16-22: "Our data agree with the systematics of these two studies, with each un-corrected dataset exhibiting similar linear regressions, except for the value of the y-intercepts, and the slope of the current data being slightly exaggerated relative to the other data-sets (see Fig. 3). Although the previously published data for the North Atlantic Ocean have nearly-identical linear regressions, an offset of +0.11 ‰, relative to the de Souza et al., (2012b) data was observed and discussed by Brzezinski and Jones (2015), concluding that an analytical bias existed."

(2) We modified the following text on page 8 Line 1: 'Factoring out the offset in absolute $\delta^{30}Si_{DSi}$ values and the greater variability in our data (see Fig. 3 for details).

(3) The figure caption for Fig. 3 (was Fig. 4) now includes the following information regarding the statistics associated with the linear regressions: "The statistics associated with each linear regression are as follows: de Souza et al. (2012b) – standard deviation of the slope (SDs) = 0.31, standard deviation of the y (SDy) = 0.06, standard deviation of the intercept (SDi) = 0.02, R2= 0.86, n=58; Brzezinski and Jones (2015) - SDs = 0.32, SDy = 0.07, SDi = 0.02, R2= 0.83, n=83; these results – SDs = 1.1, SDy = 0.17, SDi = 0.08, R2= 0.64, n=29." on Page 21 Lines 18-22.

(4) In addition, I noticed that one data point was missing from the supplementary table (although had been included in Fig.3) and that several data points were missing from Fig. 3

for the depth range between 1000-1500m. These data were available in the supplementary table, but not in the original regression calculations. This is why the slope has become slightly more positive in the new Fig. 3 (was Fig. 4)

- Fig. 5d is a key figure and is much too small when printed. Moreover the DSi concentration is missing. I suggest to restrict Fig. 5 to the current panels a, b, c and to add a fig. 6 with current panel 5d + a panel with DSi concentration. Alternatively, Fig. 5 could cover a full A4 page and not just less than half of it. **We have split Figure 5abc (now Fig. 4) and have made a new Fig. 5d (now Fig. 5b) and included silicic acid data (Fig. 5a) alongside Fig 5b. Both (new) Figures 4 and 5 are also plotted against longitude.**

- Could the authors provide a table with d30Si and DSi end-members of water masses C2 as calculated from their isotopic data and the contribution based on OMP from Garcia-Ibanez et al. (2017)? This would be very useful. **We have provided two supplementary tables (Table S3 and S4) with relevant information regarding DSi end members based on the OMP from** García-Ibáñez **et al., 2018. Table S3 provides all of the details regarding the DSi end members for the different water masses. Table S4 provides all of the d30Si values presented in this manuscript alongside the relevant information for each water mass at each sampling location. In addition, previously published values for AABW, LSW, DSOW, and AW are presented in Fig. 3 (was Fig. 4). The text referring to the endmembers in the figure caption is on page 21 Lines 22-24 and reads as: 'The stars presented in this figure represent the end-members for the AABW, LSW, and DSOW previously published by de Souza et al. (2012b – grey stars), the Arctic Water (AW) previously published by Brzezinksi and Jones (2015 – the black star), and an unknown end-member (blue star)."**

- Supplementary Table S1: provide in the Table caption the definition of Si = DSi – NO3.* **This definition was added to the supplementary Table S1 caption. In addition, we defined DSi as dissolved silicon in the caption for Table S1 and we added one data point that did not appear in the Table in the previous submission, although it did appear in older version of Fig. 5.**

Grasse Review

P1 L12: I think the information that low DSI samples could not be measured does not necessarily need to be in the Abstract. I think it would be more important that this information is mentioned in the methods or results part. **We have removed the text in the abstract (Page 1 Lines 11-12) and have added the text to the results section (Page 6 Line 27-28).**

P3 L20: Mesh size of the AG 1 X8 resin? **The text "(100-200 mesh size)" was added to the manuscript (Page 3 Line 20).**

P5 L15: It seems the manuscript Garcia-Inánez et al. is already accepted. **This was not the case at the time of submission and has now been changed (Page 5 Line 15, Page 10 Line 7, Page 16 Line 10-12, Page 21 Line 7).**

P6 L5: Please include one sentence about the DSI concentrations in the upper 500 m and that the samples could not be analyzed. **Text has been added on Page 3 Lines 5-7: 'Dissolved silicon (DSi) concentrations were measured throughout the water column (Fig. 2, Supplementary Table S1), but only the samples collected below 500 m are discussed since no $\delta^{30}Si_{DSi}$ samples were collected from within the upper water column.'**

P6 L18: Please give the exact values of the lowest δ30dSi (0.95 ‰ to 0.98 ‰. I think these very low δ30dSi values are actually quite interesting and need some more attention. See my comments below. **We have added text on Page 6 Line 20: "0.95 ‰ and 0.98 ‰, respectively"**

P7 L13: I think it would be helpful to modify figure 4. First of all, you should make your data more visible (e.g., bring your data to the front, use a light color for the already published data). You could try to group your data.e.g., only use open ocean stations vs. stations close to landmasses. Colorcode the stations or samples that are characterized by specific water masses. It would also be helpful to add water mass end members, e.g., AABW, which brings a light source from the south 1.2 ‰ (0.01 DSi; Souza et al. 2012). That could show additional processes that influence your deep-water masses e.g. at St. 1 and St. 13. Generally, I think it is interesting, that you see such light δ30dSi values and it should be discussed in more detail. According to your intercalibration with de Souza et al. (Fig. 6) and your results from the intercalibration study Grasse et al. (2017) your δ 30dSi data agrees very well within error (0.1 ‰ 2sd). Therefore, a water sample of 1 ‰ together with slightly higher DSi compared to de Souza et al., might indicate that further emineralization influences the δ30dSi composition. Such low (or even lower, 0.6 ‰ values are ypically associated with much higher DSi of 130 to 150 micromol in the Pacific and (Reynolds et al.2006, de Souza et al., 2012, Grasse et al., 2013) at DSi concentrations (even though I know that some people doubt some of the δ 30dSi deep water values in the North Pacific). However, Grasse et al. 2016 observed δ30dSi values of 1.1 ‰ in bottom water of the Peruvian shelf (â Li j40 micromol), which were influenced by pore waters from the sediment and remineralization at the sediment-seawater interface (Ehlert et al., 2016). Not necessary an effect you observe, but if not dissolution at the seawater-sediment interface or in the water column influences your δ 30dSi, you could also have admixture with a distinct water mass that brings in a very light δ30dSi signature (e.g., a water masses from Iceland? I am not so familiar with the water mass circulation in the Atlantic, but it seems that the NEADW can pick up its signature here?). Additionally, the circulation is quite sluggish, or? Therefore, you can have a trapping effect? I do not want, that you go too much into detail into the Pacific seawater δ 30dSi distribution and I also see that some of the values are identical within error, but I would like to have a better explanation why not all of your data does fall on the line for DSi versus δ 30dSi. **We have taken into consideration the recommendations made by the reviewer and have made the following changes:**

(1) The suggested changes (colour coding, end-members, etc.) made by the reviewer for Fig. 4

(now Fig. 3) have been made. See Fig. 3 for modifications. In addition, after I received the reviews, I noticed that one data point was missing from the supplementary table (although had been included in Fig.4 – now Fig. 3) and that several data points were missing from Fig. 4 for the depth range between 1000-1500m. These data were available in the supplementary table, but I will now include them in the new Fig. 4 (Fig. 3). The lack of these data did modify the linear regression for this study, and the appropriate statistics were applied and discussed (see Cardinal Review regarding Fig. 4 (now Fig. 3) for details on the changes made to the manuscript).

(2) The text referring to the endmembers in the figure caption is on page 21 Lines 22-25 and reads as: 'The stars presented in this figure represent the end-members for the circumpolar deep water (CDW), LSW, and DSOW previously published by de Souza et al. (2012b – grey stars), the Arctic Water (AW) previously published by Brzezinksi and Jones (2015 – the black star), and an unknown end-member (blue star)."

(3) The following text has been added to Page 10 Lines 16-17: "Interestingly, four of our deep samples from stations 1 and 13 have low $\delta^{30}Si_{DSi}$, perhaps indicative of another unknown source of isotopically light DSi (see Fig. 3). However, this still needs to be confirmed."

P7 L8: Please give the values (low, high) for the study by de Souza et al. **These changes have been added to Page 7 Lines 12-13: "from high values (>2.0 ‰) in the Si-poor waters that contribute to NADW to low values (1.2 ‰).**

P7 L25: please mention here (or at least above) the absolute δ30dSi values from the study of de Souza et al. for comparison with your values. The range can be similar, but that does not necessarily mean, that the δ30dSi are identical. **This was addressed in the question above.**

P10 L8: Please also explain, why the uppermost sample at station 26 has such high δ30dSi. **We have added the following text on Page 10 Line 23-24 – "At a depth of 500 m the $\delta^{30}Si_{DSi}$ value (+2.85 ‰) is our most elevated isotopic composition, which may be influenced by the SAIW, but this is difficult to argue since this sample site is the only partial sample from this water mass."**

P11 L5: Please mention the stations you are talking about. High δ30dSi? Value? What values? **We have added the following text on Page 11 Line 19 – "..(e.g. STN 77, 502 m).."**

P11 L10: What are the δ 30dSi values in the Labrador Sea? Please make clear that it is subducted surface water. **We have added the following text on Page 11 Lines 24-25 – "(stations 64, 69, 77), which consists primarily of subducted surface water."**

P11 L24: Please give me the station number and depth that makes it much easier to follow and understand your discussion. **We have added the following text on Page 12 Line 6 – "..predominantly DSOW (STN 44, 2900 m).."**

P11 L25 Doesn't NEADW has high DSi? Here I am getting confused, isn't the NEADW influencing the eastern deep waters? At least according to Fig 4. in Garcia-Ibanez et al.? Please check the Garcia-Ibanez paper for water masses; it seems that there are some discrepancies, most likely as a result of the review process of the manuscript. **As mentioned in the response to reviewers (starting page 5 Line 31), NEADW recirculates in the West European Basin and mixes with the surrounding waters, including the Antarctic Bottom Water (AABW) (van Aken and Becker, 1996), resulting in the formation of LDW. The concentration of DSi in the NEADW is. NEADW is the dominant water mass for the deep Eastern area of OVIDE. As answered in the previous comment, NEADW is derived from ISOW so it is consistent to have similar d30Si in both ISOW and NEADW.**

Fig.2 I do not think that the Figures has to be in the Paper. In my opinion, it is enough to mention in the text, that all samples fall on the mass-dependent fractionation line. **We have made the changes recommended by the reviewer and have removed Fig. 2.**

Fig4: Can you please adjust the y-scale from 0.5 ‰ to 2 ‰. Please add the studies indicated by different color directly to the legend. Would be good to modify the figure (see comments above) C4 **These changes have been made (see Fig. 3).**

Fig. 5: It is quite tricky to distinguish the colors of different water mass types. You could only name the dominant water mass in the figure. Similar to Garcia-Ibanez et al. (Figure 4). Can you replace section distance with longitude? **These changes have been made (see Fig. 5).**

The following is a list of the relevant changes made in the manuscript described by page number. Note that all of the major changes are also indicated in the point by point response to reviewer comments.

The original **Figure 2** was removed and therefore the **figure captions for Figures 2-5 were changed** (see page 21 and 22 for modifications to figure captions)

Figure 4 (now Figure 3) was heavily modified. This figure now has (1) more data (data was available in the original supplementary table), (2) a modified linear regression for the current study's data (discussion was also modified – see below), (3) end-members for different water masses, (4) colour-coded data by station number for this study, and (5) relevant information (e.g. citation and linear regressions) for the two published data sets shown alongside the current data. The Figure caption (page 21) for this figure was modified to account for these changes and text was added for the discussion (page 7, see below) of these changes.

Figure 5abc (now Figure 4) was modified by splitting panels a, b, and c from panel d. Also, the x-axis is now represented by longitude instead of section distance.

Figure 5d (now Figure 5b) was split from Fig 5abc and a new panel (a) was added with silicic acid concentration data.

<u>Page 1</u>
Inserted "(GEOTRACES GA-01)"| in the Abstract and in the Title
Deleted "Near-surface water δ30SiDSi could not be evaluated due to the very low dissolved silicon (DSi) concentrations (< 5□M). However, v"

<u>Page 2</u>
Inserted "(GEOTRACES GA-01) in the introduction

<u>Page 3</u>
Inserted "100-200mesh size"

<u>Page 4</u>
Inserted "(d29SiNBS28 = 0.52 × d30SiNBS28)
Deleted "Fig. 2"

<u>Page 6</u>
Inserted "(on (DSi) concentrations were measured throughout the water column (Fig. 2a, Supplementary Table S1), but only the samples collected below 500 m are discussed since no $\delta^{30}Si_{DSi}$ samples were collected from within the upper water column."
Inserted "0.95 ‰ and 0.98 ‰, respectively"
Inserted "Near-surface water $\delta^{30}Si_{DSi}$ could not be evaluated due to the very low dissolved silicon (DSi) concentrations (< 5"µM)

<u>Page 7</u>
Inserted "(>2.0 ‰)"
Inserted "(1.2 ‰)"
Changed the third paragraph to: Our data agree with the systematics of these two studies, with each un-corrected dataset exhibiting similar linear regressions, except for the value of the y-intercepts, and the slope of the current data being slightly exaggerated relative to the other data-sets (see Fig. 3).

Although the previously published data for the North Atlantic Ocean have nearly-identical linear regressions, an offset of +0.11 ‰, relative to the de Souza et al., (2012b) data was observed and discussed by Brzezinski and Jones (2015), concluding that an analytical bias existed. Such offsets of order ±0.2 ‰ have been recognized to exist between seawater δ^{30}Si data produced in different laboratories (Grasse et al. 2017); their origin remains unclear, although they may have to do with differences in sample processing and chemical purification. The offset of the new data to that of de Souza et al. (2012b), produced at ETH Zurich, is somewhat surprising given the good agreement in $\delta^{30}Si_{DSi}$ for 6 seawater samples analyzed both at Plouzané and Zurich, but a small offset to lower $\delta^{30}Si_{DSi}$ at Plouzané is consistent with the offset (0.1 ‰) in these two laboratories' mean $\delta^{30}Si_{DSi}$ values for the seawater reference Aloha-1000 (Grasse et al., 2017). Whilst not ideal for the determination of the absolute $\delta^{30}Si_{DSi}$ value for each basin, the existence of such interlaboratory offsets does not impair our ability to analyze the distribution of $\delta^{30}Si_{DSi}$ along the GEOVIDE transect, with the systematics of our data exhibiting similar behaviour to previously-published studies (Fig. 3).

Page 7
Inserted "and the greater variability in our data (see Fig. 3 for details)."

Page 10
Replaced STN with stations
Inserted "Interestingly, four of our deep samples from stations 1 and 13 have low □$^{30}Si_{DSi}$, perhaps indicative of another unknown source of isotopically light DSi (see Fig. 3). However, this still needs to be confirmed."
Inserted "a depth of 500 m, the $\delta^{30}Si_{DSi}$ value (+2.85 ‰) is our most elevated isotopic composition, which may be influenced by the SAIW, but this is difficult to argue since this sample site is the only partial sample from this water mass, At"

Page 11
Inserted "(e.g. STN 77, 502 m)"
Inserted "and Fig. 5"
Inserted (stations 64, 69, 77), which consists primarily of subducted surface water"

Page 12
Inserted "predominantly" and "(STN 44, 2900 m)"

Page 16
Deleted " García-Ibáñez, M.I., Pérez, F.F., Lherminier, P., Zunino, P., Tréguer, P., in review: Water mass distributions and transports for the 2014 GEOVIDE cruise in the North Atlantic, Biogeosciences Discuss., doi:10.5194/bg-2017-355, 2017.
Inserted "García-Ibáñez, M. I., Pérez, F. F., Lherminier, P., Zunino, P., Mercier, H., and Tréguer, P.: Water mass distributions and transports for the 2014 GEOVIDE cruise in the North Atlantic, Biogeosciences, 15, 2075-2090, https://doi.org/10.5194/bg-15-2075-2018, 2018."

Page 22
Acknowledgements - a few changes were made here as well.

Supplementary Tables
Two additional supplementary tables were created to support the data shown in Figures 3 and 4.

The silicon stable isotope distribution along the GEOVIDE section (GEOTRACES GA-01) of the North Atlantic Ocean

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Abstract. The stable isotope composition of dissolved silicon in seawater ($\delta^{30}Si_{DSi}$) was examined at 10 stations along the GEOVIDE section (GEOTRACES GA-01), spanning the North Atlantic Ocean (40°N-60°N) and Labrador Sea. Near-surface water $\delta^{30}Si_{DSi}$ could not be evaluated due to the very low dissolved silicon (DSi) concentrations (< 5 µM). However, vVariations in $\delta^{30}Si_{DSi}$ below 500 m were closely tied to the distribution of water masses. Higher $\delta^{30}Si_{DSi}$ values are associated with intermediate and deep water masses of northern Atlantic or Arctic Ocean origin, whilst lower $\delta^{30}Si_{DSi}$ values are associated with DSi-rich waters sourced ultimately from the Southern Ocean. Correspondingly, the lowest $\delta^{30}Si_{DSi}$ values were observed in the deep and abyssal eastern North Atlantic, where dense southern-sourced waters dominate. The extent to which the spreading of water masses influences the $\delta^{30}Si_{DSi}$ distribution is marked clearly by Labrador Sea Water (LSW), whose high $\delta^{30}Si_{DSi}$ signature is visible not only within its region of formation within the Labrador and Irminger Seas, but also throughout the mid-depth western and eastern North Atlantic Ocean. Both $\delta^{30}Si_{DSi}$ and hydrographic parameters document the circulation of LSW into the eastern North Atlantic, where it overlies southern-sourced Lower Deep Water. The GEOVIDE $\delta^{30}Si_{DSi}$ distribution thus provides a clear view of the direct interaction between subpolar/polar water masses of northern and southern origin, and allow examination of the extent to which these far-field signals influence the local $\delta^{30}Si_{DSi}$ distribution.

1 Introduction

Proxies of nutrient utilisation, such as the silicon stable isotopic composition ($\delta^{30}Si$) of diatom silica, provide a means of reconstructing the past behaviour of marine nutrient cycles, giving insight into the strength of the biological pump in the past, and its influence over atmospheric concentrations of CO_2. However, diatom silica $\delta^{30}Si$ does not depend solely on the degree of utilisation of dissolved silicon (DSi) at the ocean's surface, but also on the $\delta^{30}Si$ value of its source DSi. Since the $\delta^{30}Si$ of DSi ($\delta^{30}Si_{DSi}$) at any given location in the ocean results from the combined effects of biological uptake of dissolved silicon, dissolution of sinking biogenic silica, and meso- to macro-scale features of ocean circulation, successfully reconstructing past silica cycling from the variations in $\delta^{30}Si$ of diatoms accumulating in sediments requires a reasonable understanding of the processes that control the $\delta^{30}Si_{DSi}$ distribution.

Significant progress has been made in this regard by fifteen years' worth of work in the Southern Ocean (Varela et al. 2004; Cardinal et al., 2005; De La Rocha et al., 2011; Fripiat et al., 2011), in the North, Equatorial and South Pacific (De La Rocha et al., 2000; Reynolds et al., 2006; Beucher et al., 2008; 2011; de Souza et al., 2012a), and recently in the Arctic Ocean (Varela et al., 2016), in conjunction with various models (De La Rocha and Bickle, 2005; Reynolds, 2009; Coffineau et al., 2014), not the least of which are global circulation models (Wischmeyer et al., 2003; de Souza et al., 2014; 2015; Holzer and Brzezinski, 2015). It is now widely understood that fractionation of silicon isotopes during uptake and biomineralization of silica in surface waters increasingly elevates the $\delta^{30}Si_{DSi}$ in surface waters (De La Rocha et al., 1997; Sutton et al., 2013). At the same time, dissolution of biogenic silica exported to deeper layers works to enrich them in dissolved silicon of lower $\delta^{30}Si_{DSi}$ (Demarest et al., 2009; de Souza et al., 2014; Wetzel et al., 2014). For many deep waters of the ocean, the mixing between water masses of vastly different origin (and thus different $\delta^{30}Si_{DSi}$) as they circulate through the ocean basins plays a much greater role than the dissolution of sinking biogenic silica in setting geographic patterns in deep ocean $\delta^{30}Si_{DSi}$ (de Souza et al., 2014).

This is particularly true of the deep Atlantic Ocean, which displays a notable north-south gradient in both the concentrations of dissolved silicon (from < 10 µM in the North Atlantic to > 125 µM in the South Atlantic) and its $\delta^{30}Si_{DSi}$ (from roughly +1.9 ‰ in the North Atlantic down to +1.2 ‰ in the South Atlantic) (de Souza et al., 2012b; Brzezinski and Jones, 2015). Based on modeling results (de Souza et al., 2014), the bulk of the change in $\delta^{30}Si_{DSi}$ occurs mainly in the northern North Atlantic for reasons that are unique to this area of the ocean. The Labrador Sea, located between Greenland and the North American continent, is a key site contributing to the formation of North Atlantic Deep Water (NADW). The surface waters that cool in this region and sink to form Labrador Sea Water (LSW), an important component of NADW, are nutrient-poor. This means that their DSi concentration is markedly low and its $\delta^{30}Si_{DSi}$ is notably high, characteristics that are imparted to the deep water mass during formation. Its low DSi concentration makes the $\delta^{30}Si_{DSi}$ of deep water in this area very susceptible to change via the addition of dissolved silicon by mixing or dissolution of opal. Unfortunately, only one depth profile of $\delta^{30}Si_{DSi}$ is currently available for the entire Labrador Sea DSi (de Souza et al., 2012b). Even without taking into account its dynamic nature, the North Atlantic bears better mapping of the $\delta^{30}Si_{DSi}$ of its waters.

Recently, we began rectifying the situation via an internationally-funded **GEO**TRACES campaign (GEOTRACES GA-01) that was carried out along the O**VIDE** section of the North Atlantic Ocean and Labrador Sea (GEOVIDE). We use the $\delta^{30}Si_{DSi}$ distribution to constrain the processes that influence the distribution and cycling of silica in the North Atlantic Ocean and Labrador Sea.

2 Materials & Methods

2.1 Sample collection and processing

Samples were collected aboard the R/V *Pourquoi Pas?* during GEOVIDE. The cruise began on May 15, 2014 in Lisbon, Portugal, headed north towards Greenland, and then traversed south-west to St. John's, Canada, arriving on June 30, 2014 (Fig. 1).

Seawater samples for $\delta^{30}Si_{DSi}$ analysis were collected using Niskin bottles attached to a standard rosette conductivity-temperature-depth (CTD) unit from 10 locations in the North Atlantic Ocean and Labrador Sea (Fig. 1 and Table 1). Samples were filtered through polycarbonate 0.45 μm filters (Millipore) and stored in acid-cleaned, low-density polyethylene bottles at room temperature.

The DSi concentration of all samples collected (n = 56) was determined via molybdate blue spectrophotometry (Strickland and Parsons, 1972). For the measurement of $\delta^{30}Si_{DSi}$, DSi was extracted from the seawater by precipitating it as trimethylamine silicomolybdate, which was subsequently combusted to form SiO_2 (De La Rocha et al., 1996). This SiO_2 was dissolved at room temperature in polypropylene microcentrifuge tubes (1.5 mL) containing 23 M HF (Suprapur) to yield a final solution concentration of 0.23 M Si (e.g. 4 μmol of SiO_2 dissolved in 17.4 μL of HF).

2.2 Purification

Every sample was further purified using ion exchange chromatography following Engström et al. (2006). Briefly, 17.4 μL of a 0.23 M Si solution was diluted in 7.7 mL of Ultra Hiqh Quality water (UHQ H_2O; 18.2 MΩ-cm; Millipore Direct-Q) and loaded onto columns containing AG-1-X8 resin (100-200 mesh size, BioRad) that had been preconditioned with 2 M NaOH. The sample matrix was eluted using 95 mM HCl + 23 mM HF followed by the elution of the purified Si using 0.14 M HNO3 + 5.6 mM HF. All acids were Suprapur (Merck) and were diluted with UHQ H_2O.

2.3 Isotopic measurements

Silicon stable isotope composition ($\delta^{30}Si$) of the purified samples was measured using standard-sample bracketing combined with external normalisation by doping the samples with magnesium (Mg) (e.g., Cardinal et al., 2003) on a Thermo Scientific *Neptune* multi-collector inductively-coupled plasma mass spectrometer (MC–ICP-MS) at the Unité Géosciences Marines (Ifremer, Plouzané). Prior to the isotopic analysis, the purified samples were diluted with 0.16 M HNO_3 (1 % HNO_3) to 1 ppm Si, yielding a roughly 12 V signal on mass 28 at medium resolution (see Table 2 for additional information on operating conditions). All samples and standards (NBS28 and a 99.995 % pure silica sand (Alfa Aesar) used as a working standard) were passed through column chemistry and matrix-matched to give the same signal strength (within 10 %) and to contain the same amount of HF (generally 1 mM). Magnesium (1000 ppm, NIST SRM) was added to the samples and standards just prior to measurement at a final concentration of 0.1 ppm (Cardinal et al., 2003; Abraham et al., 2008). Si solutions were introduced into the plasma via an Apex desolvating system equipped with a PFA nebulizer (uptake rate = 100 μL min^{-1}) without additional gas.

For each measurement, beam intensities at masses 25 and 26 (Mg), and 28, 29, and 30 (Si) were monitored in dynamic mode (i.e. switching between Si and Mg masses) for one block of 25 cycles of 8-second integrations. Five minutes of rinse with 2 % HNO_3 followed each sample and each standard solution. Solutions were analyzed in medium resolution mode (m/Δm > 6000). Using a standard-sample-standard bracketing technique, $\delta^{30}Si$ values for the samples were expressed as follows:

$$\delta^{30}Si\ (‰) = [(^{30}Si/^{28}Si)/(^{30}Si/^{28}Si)_{standard})-1] \times 1000 \qquad (1)$$

The Si isotope ratios in Eqn. 1 above ($^{30}Si/^{28}Si$ and $^{29}Si/^{28}Si$) were corrected for mass bias by external normalisation using Mg doping. For example, the corrected ^{30}Si to ^{28}Si ratio $(^{30}Si/^{28}Si)_{corr}$ is:

$$(^{30}Si/^{28}Si)_{corr} = (^{30}Si/^{28}Si)_{meas} \times (^{30}Si_{AM}/^{28}Si_{AM})^{\varepsilon Mg} \qquad (2)$$

Where $(^{30}Si/^{28}Si)_{meas}$ is the measured ratio, $^{30}Si_{AM}$ and $^{28}Si_{AM}$ are the atomic masses of ^{30}Si and ^{28}Si. ε_{Mg} is calculated from the beam intensities on masses 25 and 26 :

$$\varepsilon_{Mg} = \ln [(^{25}Mg_A/^{26}Mg_A)/(^{25}Mg/^{26}Mg)_{meas}]/[^{25}Mg_{AM}/^{26}Mg_{AM}] \qquad (3)$$

where $^{25}Mg_A/^{26}Mg_A$ is the expected ratio of the natural abundances of the isotopes, $(^{25}Mg/^{26}Mg)_{meas}$ is the measured ratio, and $^{25}Mg_{AM}$ and $^{26}Mg_{AM}$ are the atomic masses of ^{25}Mg and ^{26}Mg respectively. Each measurement of a sample fell between two measurements of the standard, and each sample was measured three times. This total of three sample measurements and five standard measurements was repeated 2-3 times in each mass spectrometry session and used to calculate one replicate value of $\delta^{30}Si$ and $\delta^{29}Si$. As discussed below, full chemistry replicates were routine for each sample (see Table S2).

Interference-free measurement was ensured by checking that $\delta^{29}Si$ and $\delta^{30}Si$ for all samples was consistent with the mass dependent fractionation line ($\delta_{29}Si_{NBS28} = 0.52 \times \delta^{30}Si_{NBS28}$)~~(Fig. 2)~~. The signal was optimized to reduce the $^{14}N^{16}O$ interference on m/z 30 to below 0.5 % of the ^{30}Si peak. Measurements were performed on the low-mass side of the peak where interference is minimal. Blanks were maintained below 1 % of the main signal and were subtracted for each sample and standard. Long-term reproducibility and accuracy on $\delta^{30}Si$ values of the analytical procedure were assessed using the standard deviation of 54 analyses of NBS28 and 29 analyses of a secondary reference standard (Silicon (IV) oxide, Alfa Aesar) generated over 6 years

(±0.10 ‰, 2σ). Reproducibility of the full chemical and analytical procedure was estimated using at least one replicate of each sample (chemical preparation plus isotopic measurements) and average reproducibility on replicate δ^{30}Si was ±0.10 ‰ (2σ). Measurements of Big Batch (n = 3) produced an average value of -10.48 ± 0.34 (2σ), well within the range of intercalibration values reported by Reynolds et al. (2007). Measurement of the US GEOTRACES intercalibration reference seawater standard from the Aloha Station (1000 m) gave a $\delta^{30}Si_{DSi}$ value of +1.16 ± 0.16 ‰ (2σ, n = 3), within the range of intercalibration values (1.24 ± 0.20 ‰; Grasse et al., 2017). Measurement of the Canada/GEOVIDE GEOTRACES intercalibration samples, where duplicate samples at 3 depths and 2 stations were analysed by two different laboratories (Ifremer Plouzané and ETH Zurich), conforming to the GEOTRACES intercalibration protocol for a cruise without a cross-over station, gave similar $\delta^{30}Si_{DSi}$ values (see Table 3). Note that ETH Zurich uses a different purification method (cation exchange resin, see de Souza et al., 2012b) and MC-ICPMS instrument (Nu Plasma 1700) than Ifremer Plouzané (described in section 2.2). The methods for each laboratory that participated in Canada/GEOVIDE GEOTRACES intercalibration study are also presented in the US GEOTRACES intercalibration study (Grasse et al., 2017).

2.2 Optimum Multiparameter Analysis to determine the water mass structure in the North Atlantic Ocean

In order to accurately examine the relationship between the distribution of $\delta^{30}Si_{DSi}$ and water masses, the results of the Optimum Multiparameter (OMP) analysis of García-Ibáñez et al. (20187; this issue) were used to identify the mixture of water masses present within each sample and their contribution to the DSi budget.

The upper layers of the GEOVIDE section were represented by the North Atlantic Central Waters (NACW), transported by the North Atlantic Current (NAC; Pollard et al., 1996), and Subpolar Mode Waters (SPMW), the end-product of the transformation of NACW through air-sea interaction (McCartney and Talley, 1982; Tsuchiya et al., 1992). To account for the change in the temperature of SPMW along the path of the NAC as the result of air-sea interaction, two SPMWs were differentiated: IcSPMW (Iceland-Subpolar Mode Water) and IrSPMW (Irminger-Subpolar Mode Water). The intermediate layers of the section were represented by LSW, Mediterranean Water (MW), Subarctic Intermediate Water (SAIW), and Polar Intermediate Water (PIW). LSW is the last stage of the transformation of SPMWs and forms in the Labrador and Irminger Seas (e.g., Pickart et al., 2003; de Jong and de Steur, 2016; Fröb et al., 2016). MW enters the North Atlantic from the Mediterranean Sea through the Strait of Gibraltar (Ambar and Howe, 1979; Baringer and Price, 1997). SAIW originates in the Labrador Current by mixing of the NAC waters with LSW (Iselin, 1936; Arhan, 1990; Read, 2000). The deep layers of the section were represented by Denmark Strait Overflow Water (DSOW), Iceland–Scotland Overflow Water (ISOW), North East Atlantic Deep Water (NEADW) and Lower Deep Water (LDW). Overflow waters (DSOW and ISOW) form after the deep waters of the Nordic Seas flow over the Greenland–Iceland–Scotland sills and entrain Atlantic waters (van Aken and de Boer, 1995; Read, 2000; Dickson et al., 2002; Fogelqvist et al., 2003; Yashayaev and Dickson, 2008). NEADW is formed as a result of entrainment events that occur along the journey of ISOW through the Iceland Basin (van Aken, 2000). NEADW recirculates in the West European Basin and mixes with the surrounding waters, including the Antarctic Bottom Water (AABW) (van Aken and Becker, 1996), resulting in the formation of LDW.

3 Results

3.1 Water column profiles of DSi

Dissolved silicon (DSi) concentrations were measured throughout the water column (Fig. 2a, Supplementary Table S1), but only the samples collected below 500 m are discussed since no $\delta^{30}Si_{DSi}$ samples were collected from within the upper water column. ~~a~~ DSi concentrations below 500 m along the GEOVIDE section ranged from 7 to 47 µM (Fig. 2~~3~~a). The stations located to the east of the Mid-Atlantic Ridge (MAR; STN 01, STN 13, STN 21, STN 26, STN 32) show DSi increasing in concentration from < 10 µM to 20-50 µM below about 2000 m (Fig. ~~3~~2a). Stations located to the west of the MAR (STN 44, STN 60, STN 64, STN 69, and STN 70) show only slight increases in DSi concentration with depth, with most of the values falling between 9-12 µM (Fig. 2~~3~~a). This difference relates to the distribution of water masses in the northern North Atlantic, with the predominance of the most egregiously Si-poor northern-sourced water masses (LSW, ISOW/NEADW, DSOW) predominating in the western Atlantic while abyssal layers in the eastern Atlantic have had more of a contribution from Si-rich southern-sourced waters (LDW) (see Section 4.1). A clear pattern in the DSi concentration throughout the water column is that the eastern profiles exhibit a more typically "nutrient-like" profile than in the western profiles (Supplementary Table S1; Fig. ~~3~~2a).

3.2 Water column profiles of $\delta^{30}Si_{DSi}$

All GEOVIDE water column profiles have relatively high $\delta^{30}Si_{DSi}$ (+1.5 to +3 ‰) between 500-1000 m, and show a trend towards lower $\delta^{30}Si_{DSi}$ values with depth (although none significantly lower than +1 ‰) (Fig. 2~~3~~b). Strikingly, the lowest values of $\delta^{30}Si_{DSi}$ occur at stations nearer to the Iberian margin (e.g., STN 01, STN 13: 0.95 ‰ and 0.98 ‰, respectively), while highest values tend to occur at the upper depths of the profiles (500-1000 m) at stations north of 50°N and west of 20°~~E~~W (Stations 26, 32, 44, 60, 64, 69, 77; Fig. 2~~3~~b), mirroring the differences in DSi between these locations (Fig. 2~~3~~a, Supplementary Tables S1 and S2). Profiles of $\delta^{30}Si_{DSi}$ in the Labrador Sea (stations 64, 69, 77) show high values (above +1.5 ‰) extending below 2000 m water depth. These high values reach the bottom within the central Labrador Sea (STN 69). Elevated $\delta^{30}Si_{DSi}$ values at depths between 1000-2000 m can be found at all stations in the Irminger Basin and extend eastwards into the western portion of the West European Basin (up to STN 26), but the mid-depths of the far eastern Atlantic are marked by lower $\delta^{30}Si_{DSi}$ values around +1 ‰. Near-surface water $\delta^{30}Si_{DSi}$ could not be evaluated due to the very low dissolved silicon (DSi) concentrations (< 5 µM).

4 Discussion

4.1 North Atlantic $\delta^{30}Si_{DSi}$ systematics in a basin-wide context

The deep Atlantic Ocean below 1000 m exhibits a wide variation in DSi concentrations, ranging from ~10 µM in the mid-depths of the subpolar North Atlantic Ocean to ~120 µM in the abyssal southern Atlantic. Since at least the work of Broecker and Takahashi (1980), it has been known that this variation is primarily brought about by the quasi-conservative mixing of DSi between Si-rich abyssal waters derived from the Southern Ocean and Si-poor waters of North Atlantic origin. The analysis of Sarmiento et al. (2007), which takes the effects of water mass mixing into account, has shown that the effect of opal dissolution on deep Atlantic DSi is resolvable, but plays a near-negligible role in controlling the deep DSi distribution.

The first systematic study of the Atlantic $\delta^{30}Si_{DSi}$ distribution (de Souza et al., 2012b) showed that the quasi-conservative behaviour of DSi is clearly reflected by the $\delta^{30}Si_{DSi}$ of the deep Atlantic Ocean. Surveying deep water over a wide range of latitudes within the Atlantic Ocean, they found that values of $\delta^{30}Si_{DSi}$ vary coherently from high values (>2.0 ‰) in the Si-poor waters that contribute to NADW to low values (1.2 ‰) in the Si-rich Southern Ocean deep waters (Fig. 43). The more recent work of Brzezinski and Jones (2015) found near-identical behaviour within Atlantic deep waters along a near-zonal transect across the subtropical North Atlantic (Fig. 34).

Our data agree with the systematics of these two studies, with each un-corrected data-set exhibiting nearly identicalsimilar linear regressions, except for the value of the y-intercepts, which appear to result from a near-constant offset between $\delta^{30}Si_{DSi}$ values measured at different laboratoriesand the slope of the current data being slightly exaggerated relative to the other data-sets (see Fig. 34). Although the previously published data for the North Atlantic Ocean have nearly-identical linear regressions, anSimilar offset offset ofs +0.11 ‰, relative to the de Souza et al., (2012b) data wereas observed and discussed by Brzezinski and Jones (2015), concluding that an analytical bias existed. Such offsets of order ±0.2 ‰ have been recognized to exist between seawater $\delta^{30}Si$ data produced in different laboratories (Grasse et al. 2017); their origin remains unclear, although they may have to do with differences in sample processing and chemical purification. The offset of the new data to the dataat of de Souza et al. (2012b), produced at ETH Zurich, is somewhat surprising given the good agreement in $\delta^{30}Si_{DSi}$ for 6 seawater samples analyzed both at Plouzané and Zurich, but a small offset to lower $\delta^{30}Si_{DSi}$ at Plouzané is consistent with the offset (0.1 ‰) in these two laboratories' mean $\delta^{30}Si_{DSi}$ values for the seawater reference Aloha-1000 (Grasse et al., 2017). Whilst not ideal for the determination of the absolute $\delta^{30}Si_{DSi}$ value for each basin, the existence of such interlaboratory offsets does not impair our ability to analyze the distribution of $\delta^{30}Si_{DSi}$ along the GEOVIDE transect, with the systematics of our data exhibiting nearly identicalsimilar behaviour to previously-published studies (Fig. 34).

Factoring out the offset in absolute $\delta^{30}Si_{DSi}$ values and the greater variability in our data (see Fig. 3 for details), it is interesting to note that our deep North Atlantic samples exhibit essentially the same $\delta^{30}Si_{DSi}$ range (~0.6 ‰; Fig. 43) as that observed over the entire latitudinal range of the Atlantic Ocean (de Souza et al., 2012b). Our dataset thus indicates that DSi in the North Atlantic Ocean is an important source of isotopic variability in the deep ocean. This is at least partially due to the transport of isotopically heavy DSi to the North Atlantic by northward-flowing Subantarctic Mode Water / Antarctic Intermediate Water (de Souza et a., 2012b; 2015) and its incorporation into NADW, e.g., during the formation of LSW. However, Brzezinski and Jones (2015) hypothesized that the Arctic Ocean may also play an important role in producing deep North Atlantic $\delta^{30}Si_{DSi}$ variability, via overflows across the Greenland-Iceland-Scotland ridge (i.e., DSOW and ISOW), which dominantly contribute to Lower NADW. It thus remains to be understood how the isotopic compositions of various precursors of NADW contribute to its isotopic signal. In the following, we discuss our $\delta^{30}Si_{DSi}$ dataset in the context of regional oceanography, in order to study the control of interacting interior water masses on the $\delta^{30}Si_{DSi}$ distribution of the high North Atlantic.

4.2 Relationship between North Atlantic $\delta^{30}Si_{DSi}$ distribution and water mass structure

The GEOVIDE section intersects numerous water masses of various origins whose presence is reflected in the distributions of salinity, dissolved oxygen (O_2), and potential vorticity (PV) along the section (Fig. 45a, b, c; dissolved O_2 is presented as percent saturation, i.e., $O_2/O_2^{sat} \times 100$, where O_2^{sat} is the saturation O_2 concentration). Since $\delta^{30}Si_{DSi}$ was only measured at depths below 500 m, we focus on the intermediate and deep ocean water masses. In discussing the relationship between the $\delta^{30}Si_{DSi}$ distribution and water mass structure, we initially focus on the western- and easternmost sections of the GEOVIDE transect, where water masses are in their most unadulterated form along the transect, prior to discussing their extension into the mid-Atlantic.

Starting with the westernmost profiles, those of stationSTNs 77, 69, and 64 in the Labrador Sea, we see relatively well-oxygenated waters with low PV (Fig. 4c5) extending to depths below 2000 m, reflecting the presence of LSW. This water mass, which contributes to NADW, is formed by deep convection in the Labrador and Irminger Seas (e.g., de Jong and de Steur, 2016) and spreads across the North Atlantic at intermediate to mid-depths (see Fig. 1). Two distinct types of LSW can be distinguished and are indeed visible in our profiles. There is an extremely-low-PV ($< 4\times10^{-12}$ m^{-1} s^{-1}) and well-oxygenated (> 90 % saturation) pycnostad extending from around 400 m to 1200 m in the Labrador and Irminger Basins, and a saltier, less well-oxygenated water mass observed from roughly 1500 m to 2300 m. These two water masses have been called Upper and Lower LSW, respectively (e.g., Kieke et al., 2007), and reflect variability in the severity of heat loss and depth of convection in the Labrador Sea (Yashayaev et al., 2003; 2007) most likely associated with differences in atmospheric forcing during different phases of the North Atlantic Oscillation (NAO; Dickson et al., 1996; Lazier et al., 2002).

At the three stations in the Labrador Sea, Upper LSW has a $\delta^{30}Si_{DSi}$ of around +2 ‰ and a DSi concentration of < 10 µM (Fig 3). Lower LSW has slightly lower $\delta^{30}Si_{DSi}$ values (around +1.5 ‰) and slightly higher DSi concentrations (~10-15 µM). These differences could be due to a slightly greater proportion of regenerated silica in these deeper layers, less frequently and intensively penetrated by deep convection, or to differences in the preformed properties of Upper and Lower LSW, a result of convection to greater depths during the formation of Lower LSW.

Below LSW, the central Labrador Sea (STN 69) exhibits an exemplary "stacking" of the water masses contributing to NADW. Specifically, an increase in salinity at 3000 m points to the presence of NEADW, a modified version of the eastern Atlantic overflow water mass ISOW (van Aken and de Boer, 1995) that has crossed into the western Atlantic at the Charlie-Gibbs Fracture Zone (van Aken, 2000). At this point, NEADW has a $\delta^{30}Si_{DSi}$ of +1.5 ‰ and a DSi concentration of about 15 µM, values essentially equal to that of Lower LSW since ISOW has entrained LSW during its journey from the Iceland-Scotland sill. At the very base of the water column, beginning at about 3500 m water depth, a decrease in salinity and increase in O_2 saturation point to the presence of DSOW, which flows from the Arctic Ocean into the North Atlantic as a bottom-hugging overflow off the eastern coast of Greenland, and represents the densest water contributing to NADW (Dickson and Brown, 1994). Our $\delta^{30}Si_{DSi}$ sample is situated within the transition between NEADW and DSOW, with slightly lower DSi than in NEADW, but no distinguishable difference in terms of its $\delta^{30}Si_{DSi}$ value of around +1.5 ‰.

Moving eastwards along the GEOVIDE transect brings us next to STN 60, on the southeastern coast of Greenland. This relatively shallow station has sampled IrSPMW at its upper two depths, which have high $\delta^{30}Si_{DSi}$ values (2.8 ‰ at 1000 m and 1.8 ‰ at 1400 m) and relatively low DSi concentrations (around 10 µM), reflective of the mixing of nutrient-depleted surface waters into this water mass. Subpolar Mode Waters can be seen as precursors to LSW, as they form pycnostads of progressively greater density from east to west in the subarctic gyre, preconditioning the upper water column for deep-reaching Labrador Sea convection by producing a relatively unstratified water column (Brambilla and Talley, 2008). Their more elevated $\delta^{30}Si_{DSi}$ values than that of LSW imply that the entrainment of DSi during deep convection associated with LSW formation plays an important role in setting the final $\delta^{30}Si_{DSi}$ signature of this water mass. The deepest depth sampled at STN 60 (1800 m), on the other hand, is probably LSW, with its low PV, high O_2, and $\delta^{30}Si_{DSi}$ around +1.4 ‰, similar to the value observed in the central Labrador Sea.

Moving all the way across the Atlantic to the easternmost portion of the GEOVIDE transect allows us to focus in on two more important interior water masses. One of the most striking features in the distributions of salinity and O_2 is the tongue of salty, O_2-poor water extending westward from the Iberian margin at about 1000 m water depth. This is predominantly MW that has entered the Atlantic through the Strait of Gibraltar (Iorga and Lozier, 1999). The one sample we have of predominantly MW is at 1000 m depth at STN 01, just off of the Iberian Peninsula, with a $\delta^{30}Si_{DSi}$ of +1.2 ‰ and a DSi concentration of about 10 µM. The $\delta^{30}Si_{DSi}$ value of +1.2 ‰ corresponds well to the value of +1.3 ‰ measured by Coffineau (2013) in samples from closer to the point of origin of this water mass.

The other water mass sampled for $\delta^{30}Si_{DSi}$ in the eastern Atlantic Ocean is an O_2-poor, low-PV, Si-rich abyssal water mass that is present below about 3000 m. This is LDW (McCartney, 1992), which derives from northward-flowing AABW that has entered the eastern Atlantic Ocean via the Vema Fracture Zone (Mantyla and Reid, 1983; McCartney et al., 1991). The OMP results of García-Ibáñez et al. (201~~7~~8~~; this issue~~) shown in Fig. 5b~~d~~ nicely illustrate that LDW (which they denote as $NEADW_L$) is the dominant contributor to the DSi inventory of the deep eastern Atlantic. This is a direct result of LDW being rich in DSi (25-45 µM) when compared to the other water masses in the North Atlantic Ocean.

The influence of this Si-rich southern-sourced water mass is also clearly seen in the $\delta^{30}Si_{DSi}$ distribution (Fig. 2~~3~~b): $\delta^{30}Si_{DSi}$ values below 3000 m in the far-eastern Atlantic (station~~STN~~s. 01, 13 and 21) range from +0.95~~1.0~~ ‰ to +1.3 ‰, significantly lower than values at similar depths in the western Atlantic, which is dominated by northern-sourced water masses. The low $\delta^{30}Si_{DSi}$ values we observe for LDW compare very well with the value of +1.2 ‰ observed in AABW in the South Atlantic (de Souza et al., 2012b), indicating that the Si-richness of this water mass makes its $\delta^{30}Si_{DSi}$ value insensitive to mixing or opal dissolution as it flows northwards in the abyssal Atlantic Ocean. Interestingly, four of our deep samples from stations 1 and 13 have low $\delta^{30}Si_{DSi}$, perhaps indicative of another unknown source of isotopically light DSi (see Fig. 3). However, this still needs to be confirmed.

The remaining three stations in the mid-Atlantic (22–38°W; station~~STN~~s. 26, 32 and 44) are influenced by varying combinations of the water masses of northern and southern origin that were discussed above. The easternmost of these three stations, STN 26 at the edge of the Porcupine Abyssal Plain, provides an exemplary illustration of the interaction of these water masses. At~~ ~~ a depth of 500 m, the $\delta^{30}Si_{DSi}$ value (+2.85 ‰) is our most elevated isotopic composition, which may be influenced by the SAIW, but this is difficult to argue since this sample site is the only partial sample from this water mass, At depths of 1400 and 2000 m, the water column at this station is dominated by Lower LSW, as reflected by the PV, O_2 and salinity distributions (Fig. ~~5~~4a, b, c). As in the Labrador Sea itself, Lower LSW bears an elevated $\delta^{30}Si_{DSi}$ value, here about +1.7 ‰, and a relatively low DSi concentration of ~15 µM. This Si-poor water mass is underlain, at the very bottom of the profile (3500 m) by the Si-rich southern-sourced LDW (45 µM DSi) that bears a typically low $\delta^{30}Si_{DSi}$ value of +1.1 ‰.

The influence of dense LDW does not extend further west than the Porcupine Abyssal Plain, and thus at stations 44 and 32, Upper and Lower LSW give way to the denser ISOW (or its modified product, NEADW) with depth. As it flows over the Iceland-Scotland Ridge, ISOW mixes with more saline waters of the Atlantic thermocline to form NEADW that, being quite dense, comes to lie below LSW as it flows geostrophically along the western edge of the West European Basin (Fig. 1). The differences in DSi concentration and $\delta^{30}Si_{DSi}$ between these northern-sourced water masses are small: ISOW-influenced waters at depths of 2500-3000 m bear values of +1.4 to +1.5 ‰ for $\delta^{30}Si_{DSi}$ and 15-25 µM for DSi, whilst LSW is only slightly more DSi-poor and correspondingly higher in $\delta^{30}Si_{DSi}$ (10-12 µM and +1.4 to +1.9 ‰, respectively). The resemblance in DSi concentration and $\delta^{30}Si_{DSi}$ between these two water masses is also due to the entrainment of LSW into ISOW. Interestingly, the very base of the water column at STN 44 is occupied by the dense and Si-poor DSOW, where it has a dissolved silicon concentration of about 8 µM and a $\delta^{30}Si_{DSi}$ of +1.2 ‰. Although the DSi is typical for DSOW, the $\delta^{30}Si_{DSi}$ value of +1.2 ‰ is unexpectedly low for this water mass.

4.3 The influence of Labrador Sea Water on the North Atlantic distribution of $\delta^{30}Si_{DSi}$

The most important isotope fractionation signal in marine DSi is produced by diatom DSi uptake in the surface ocean (De La Rocha et al., 1997; Varela et al., 2004; Sutton et al., 2013), due to the dominant importance of these phytoplankton for the marine Si cycle (Tréguer and De La Rocha, 2013; Hendry and Brzezinski, 2014). As a result, elevated values of $\delta^{30}Si_{DSi}$ can be produced only within the well-lit surface ocean, where photosynthesising organisms can grow and silicify. This surface-ocean signal is communicated more broadly by the process of water mass subduction, i.e., the transport of surface water parcels into the ocean interior (Stommel, 1979). This is seen particularly clearly in our dataset, which spans a region in which exceptionally deep winter convection gives rise to mixed layers over 1 km deep in the Labrador Sea and Irminger Sea, injecting isotopically fractionated DSi into the ocean interior.

As can be seen from Figures 4 and~~-~~ 5, there is a clear association of elevated $\delta^{30}Si_{DSi}$ values with the low-PV and high-O_2 signal of LSW (e.g. STN 77, 502 m), the water mass that is produced by deep winter convection. Indeed, the eastward spread of these elevated values coincides remarkably well with the extension of LSW mapped by McCartney and Talley (1982) based on PV (as shown in Fig. 1). The influence of LSW on the North Atlantic $\delta^{30}Si_{DSi}$ distribution is also nicely illustrated by the depth profiles in Fig. 2~~3~~b and Fig. 5, which show that, unlike the eastern Atlantic with low $\delta^{30}Si_{DSi}$ values at mid-depths, the central and western North Atlantic bears elevated $\delta^{30}Si_{DSi}$ values close to those observed within the Labrador Sea itself (stations 64, 69, 77), which consists primarily of subducted surface water. Such high values at mid-depths are unique to the North Atlantic Ocean amongst the major open-ocean basins, and result from the local formation of deep waters from Si-depleted surface waters of the subpolar North Atlantic.

Thus, one proximal physical control on the North Atlantic $\delta^{30}Si_{DSi}$ distribution is the vertical transport of DSi from the surface ocean to mid-depths during LSW formation. Another physical control is shown by the close correlation between elevated $\delta^{30}Si_{DSi}$ and lower PV even within the eastern Atlantic Ocean, far from the region of deep convection (Figures 4 and~~.~~ 5). This highlights the fact that the spreading of LSW as a result of the regional circulation transports its isotopic signal within the ocean interior, resulting in mid-depth $\delta^{30}Si_{DSi}$ values around +1.5 ‰ in regions where the physical signatures of LSW can be seen, documenting the importance of water mass structure on the marine $\delta^{30}Si_{DSi}$ distribution. Furthermore, this circulation pattern results in the direct interaction of this northern-sourced water mass with the southern-sourced LDW, producing strong local $\delta^{30}Si_{DSi}$ gradients whose systematics correspond nicely to the basin-scale systematics (60°S to 60°N) documented by de Souza et al. (2012b; see Section 4.1 and Fig. 3~~4~~).

Elevated values of $\delta^{30}Si_{DSi}$ are also associated with the dense overflows from the Nordic Seas. Whilst our single sample of predominantly DSOW (STN 44, 2900 m) surprisingly bears a low $\delta^{30}Si_{DSi}$ value of +1.2 ‰, ISOW and its derivative NEADW bear similarly low DSi concentrations and similarly elevated $\delta^{30}Si_{DSi}$ values as LSW, reaching up to +1.5 ‰ in the abyssal Labrador Sea. They originate as dense bottom-hugging overflows of mid-depth Nordic Sea waters, influenced by the Arctic Ocean, that enter the North Atlantic across the submarine sills running between Greenland, Iceland and Scotland, and the elevated $\delta^{30}Si_{DSi}$ values of ISOW and NEADW reflect the isotopically-heavy nature of the deep Arctic (Varela et al. 2016). Both Brzezinski and Jones (2015) and Varela et al. (2016) suggest that this feature results from the nature of the inflows to the Arctic Ocean, which receives isotopically fractionated DSi via the upper-ocean inflows from the Atlantic (and, to a lesser extent, the Pacific) due to the shallow sills that form its boundaries to these ocean basins. Observational and modelling studies indicate that these inflows are isotopically heavy primarily due to isotope fractionation during diatom DSi uptake in the Southern Ocean, although more proximal fractionation within the Atlantic and Pacific Oceans most likely also plays some role (de Souza et al., 2012a; 2015).

Finally, interesting insights may be gained from a comparison of our Labrador Sea data with the only other published data from this region (de Souza et al., 2012b). Fig. 6 compares data from the central Labrador Sea (STN 69) from the GEOVIDE study with literature data from within the Labrador Sea and slightly further south, in the vicinity of the Grand Banks (de Souza et al., 2012b), tracing LSW and NADW as they flow southwards. The three profiles agree within uncertainty at mid-depths and below, but diverge in the upper ocean at depths associated with Upper LSW. Since deep winter convection occurs up to depths of 1000 – 1500 m regularly within the Labrador Sea, this water mass is frequently ventilated locally, which may result not only in variable physical properties (as shown in Fig. ~~5a,b,c~~4) but also changes in its chemical characteristics, such as $\delta^{30}Si_{DSi}$. However, care should be taken not to over-interpret such differences of ~0.3 ‰, given the potential for $\delta^{30}Si_{DSi}$ offsets between laboratories of ±0.2 ‰, as discussed in Section 4.1 (Reynolds et al., 2007; Grasse et al. 2017).

5 Conclusion

Water mass subduction and circulation appears to be the dominant process influencing the distribution of DSi in the North Atlantic Ocean and Labrador Sea. Our dataset of $\delta^{30}Si_{DSi}$ along the GEOVIDE transect documents the extent to which the distribution of $\delta^{30}Si_{DSi}$ in the North Atlantic Ocean and Labrador Sea is influenced by the hydrography of this region. At depths below 1000 m, the distribution of $\delta^{30}Si_{DSi}$ is clearly linked to water mass structure, with the two dominant influences coming from northern-sourced waters (LSW and ISOW) and southern-sourced waters (LDW). The Si-poor northern-sourced waters impart the intermediate and mid-depth North Atlantic Ocean with elevated $\delta^{30}Si_{DSi}$ values over +1.4 ‰ and up to +1.9 ‰, whilst the Si-rich abyssal LDW results in low $\delta^{30}Si_{DSi}$ values of +1.1 ‰ to +1.3 ‰ in the deepest eastern Atlantic Ocean. By combining our isotope data with hydrographic information and results from an optimum multiparameter analysis, we show that the $\delta^{30}Si_{DSi}$ distribution bears clear evidence of the influence of LSW flowing across the Atlantic Ocean into the eastern basins, in a manner consistent with McCartney and Talley's (1982) canonical map of the extent of this water mass. As a result, the eastern Atlantic exhibits the direct "stacking" of young, Si-poor LSW above old, Si-rich LDW, producing a range in deep ocean $\delta^{30}Si_{DSi}$ values within this one ocean basin that is comparable to that observed over the entire latitudinal range of the Atlantic Ocean and, indeed, in the global deep ocean.

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Table 1. Sampling locations from the GEOVIDE voyage in the North Atlantic Ocean and Labrador Sea (Stations 1-77) and GEOVIDE/Canada GEOTRACES intercalibration stations (Stations K1 and LS2).

Station	**Latitude (°N)**	**Longitude (°~~E~~W)**
1	40.333	-10.036
13	41.383	-13.888
21	46.544	-19.672
26	50.278	-22.602
32	55.506	-26.71
44	59.623	-38.954
60	59.799	-42.003
64	59.068	-46.083
69	55.842	-48.093
77	53.000	-51.100
K1	56.197	-53.425
LS2	60.593	-56.589

Table 2. Mass spectrometer operating conditions

Resolution	Medium
Forward Power	1200 W
Accelerating Voltage	10 kV
Plasma Mode	Dry Plasma
Cool Gas Flow Rate	15.5 L min^{-1}
Auxiliary Gas Flow Rate	0.8 L min^{-1}
Sample Gas Flow Rate	~1 L min^{-1}
Sampler Cone	Standard Ni cone
Skimmer Cone	Standard Ni cone
Desolvator	Apex (ESI)
Nebulizer	PFA microcentric nebuliser 10~~6~~0 μL min^{-1}
Running Concentrations	Si = 1-2 ppm, Mg = 1-2 ppm
Sensitivity	7-10 V ppm^{-1}
Blank Level	< 1 % signal
^{30}Si Interference	< 30 mV (usually 10-15 mV)

Table 3. Results of GEOVIDE/Canada GEOTRACES intercalibration exercise for $\delta^{30}Si_{DSi}$ (‰). Following the GEOTRACES intercalibration protocol for a cruise without a cross-over station (i.e., duplicate samples at 3 depths and 2 stations; see Table 1 for location details), the mean $\delta^{30}Si$ (± 2 standard deviations; 2SD) was analysed by two separate laboratories (ETH Zurich and Ifremer Plouzané). The difference in $\delta^{30}Si$ between the laboratories (values determined for ETH Zurich minus values determined for Ifremer/UBO) is also presented.

			ETH Zurich		**Ifremer Plouzané**		**Difference**
	Depth	**[Si]**	**δ^{30}Si (‰)**		**δ^{30}Si (‰)**		**δ^{30}Si (‰)**
Station	**(m)**	**µM**	**mean**	**2SD**	**mean**	**2SD**	
K1	300	7.79	**1.95**	0.16	**1.89**	0.17	**0.06**
K1	500	8.06	**1.79**	0.14	**1.90**	0.14	**-0.11**
K1	1000	8.34	**1.74**	0.18	**1.76**	0.16	**-0.02**
LS2	100	6.77	**1.97**	0.24	**1.92**	0.14	**0.05**
LS2	2000	9.92	**1.68**	0.12	**1.68**	0.16	**0.00**
LS2	3000	11.92	**1.72**	0.12	**1.66**	0.14	**0.06**

Figures

Figure 1. Map showing the sampling locations from the GEOVIDE voyage, overlain on a schematic of the intermediate and deep ocean circulation. Pink shading indicates the spreading of Labrador Sea Water (LSW) as documented by the extent of a water column minimum potential vorticity of 8×10^{-12} m^{-1} s^{-1} (McCartney, 1992). Dark blue arrows represent bottom-hugging Nordic Sea Overflows (ISOW and DSOW), pink arrows represent LSW, and orange arrows represent Lower Deep Water (McCartney, 1992; Dickson and Brown, 1994; Lambelet et al., 2016; see also García-Ibáñez et al., 20187; this issue).

Figure 2. Mass-dependent fractionation line of $\delta^{29}Si$ vs. $\delta^{30}Si$ (‰ vs. NBS28) for samples (n = 44) collected from 10 depth profiles in North Atlantic Ocean and Labrador Sea. MDF line represented by $\delta^{29}Si=0.52*\delta^{30}Si$, $R^2=0.99$, 2 SD=0.16 ‰ $\delta^{30}Si$.

Figure 3. Depth profiles of (a) Si concentration and (b) $\delta^{30}Si_{DSi}$ values for the North Atlantic Ocean and Labrador Sea. Nutrient data collected during the GEOVIDE cruise from a separate cast are indicated as dashed lines (see Supplementary Table S1).

Figure 34. $\delta^{30}Si_{DSi}$ versus the inverse of DSi concentration for this study (black coloured circles identified by station (STN)), de Souza et al. (2012b; grey circles) and Brzezinksi and Jones (2015; open circles) for waters > 1000 m depth. Equations reported in the figure refer to linear regressions produced for each dataset (de Souza et al.,2012b - grey line, y=6.42x + 1.14; Brzezinksi and Jones, 2015 – thin black line, y=6.53x + 1.36; this study – thick black line, y=8.18x +0.89). The statistics associated with each linear regression are as follows: de Souza et al. (2012b) – standard deviation of the slope (SDs) = 0.31, standard deviation of the y (SDy) = 0.06, standard deviation of the intercept (SDi) = 0.02, R^2= 0.86, n=58; Brzezinski and Jones (2015) - SDs = 0.32, SDy = 0.07, SDi = 0.02, R^2= 0.83, n=83; these results – SDs = 1.1, SDy = 0.17, SDi = 0.08, R^2= 0.64, n=29. The stars presented in this figure represent the end-members for the AABW, LSW, and DSOW previously published by de Souza et al. (2012b – grey stars), the Arctic Water (AW) previously published by Brzezinksi and Jones (2015 – the black star), and an unknown end-member (blue star).

Figure 45. Depth section across the GEOVIDE transect with hydrographic parameters (a) salinity, (b) oxygen (O_2) saturation and (c) and potential vorticity (PV). Spreading of Labrador Sea Water, reflected in hydrography by low-salinity, low-PV, high-O_2 signals (panels a,b,c).,

Figure 5. Depth section across the GEOVIDE transect with (a) silicic acid concentration (dissolved silicon or DSi) together with (db) $\delta^{30}Si_{DSi}$ data overlain by pie charts of the fraction of DSi in each sample contributed by various water masses, as calculated by OMP analysis (García-Ibáñez et al., 20178; this issue). Spreading of Labrador Sea Water, as shown inreflected in hydrography by low-salinity, low-PV, high-O_2 signals (Fig. 4 panels a,b,c) and in the OMP results by a dominant Si

contribution from this water mass (panel db), produces a mid-depth extension of elevated δ^{30}Si values into the eastern Atlantic (panel bd). For water mass abbreviations see main text (Section 2.4).

Figure 6. Data from the Labrador Sea (STN 69; blue) during GEOVIDE cruise (2014) compared with data from samples collected in 2010 from nearby stations in the Labrador Sea (green) and at the Grand Banks (orange) (stationSTNs. 8 and 11 in de Souza et al. (2012b).

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