Reply to Interactive comments on

“Seismic imaging of a thermohaline staircase in the western tropical North Atlantic”

We would like to thank all reviewers for the time, effort, and interest taken to review our work. Their comments helped improve the manuscript. We revised the manuscript following the suggestions of the reviewers. The original text from the different reviewers is reproduced below followed by our response (in red) to each comment.

Ilker Fer, on behalf of co-authors

Reply to Anonymous Referee #1

I think this paper should be improved leading to publication in Ocean Science. The topic is as described in the title, and is interesting.

The paper presents data and interpretation including parallel supporting analysis. However, the argument is somewhat by example: there is no real demonstration that all staircases have been detected, and the evidence that the identified feature is a staircase is rather circumstantial.

We thank the reviewer for encouraging and valuable comments. We have benefited from several, but non-coincident, data sets in our presentation and interpretation. The lack of simultaneous hydrography and seismic surveys hampers a detailed demonstration and complete identification of the thermohaline staircase. However, several threads of evidence we present in the paper show that staircase steps are not circumstantial but are well-imaged consistent with the hydrography.

I was left unsure whether a local lack of internal waves enabled the identified staircase, or if the existence of the staircase inhibited internal waves. (The introduction rather suggests the latter through cited literature).

This comment also relates to the second comment of Barry Ruddick (the "chicken/egg hypothesis" about internal waves and staircases). When conditions are favorable for both shear-induced turbulence and double diffusion, the presence of turbulence shadows the signature of staircases. Elevated level of internal wave energy is expected to lead to enhanced turbulence and diapycnal mixing, hence inhibiting staircases. We clarified this point in the revised manuscript. However, whether weak internal waves allow the formation of the staircase, or the double-diffusive convection of the staircase suppresses the internal waves by filtering out the short wavelength of the internal wave field is not known at this time (neither can it be resolved with the present data set). We clarified this in our conclusions.

In a final version I would like to see some care to make the English more readable in detail, and some of the punctuation is strange. Quite a lot of detailed comments follow.

We improved the language and style in the revised version (details are not listed).

Page 362 line 11. Delete “within”.

Done. The sentence is revised as: “Hydrography sampled in previous surveys suggests that the layers are a permanent feature of the region.”

Page 364 line 15. It is not clear here where this 10 m horizontal resolution comes from (and I am not expert). Resolution is not the same as sampling interval and in the horizontal it is not ~ λ/4 either. I am told it can be better than the Fresnel zone resolution (λh/2)**1/2 but that needs justification. [Here λ is a sound wavelength and h the depth of the reflector].

In this paragraph, when we introduce the salient features and applications of seismic reflection method we refer to “order 10 m horizontal resolution”. As the reviewer notes, the horizontal resolution issue needs further clarification and discussion. However, we choose to give this detail (which can distract the reader in the introduction) later in section 2.1 (Experimental methods / Data). The text added to section 2.1 is given in our reply to the comment for Page 367 line 8 below. Here, in the introduction we revise as “.. revealing exceptional detail between 10 - 100 m horizontal resolution..”. We further specify the resolution of our data set in section 2.1 by clarifying from “Reflected energy was recorded on a 4.1-km-long streamer containing 164 hydrophone groups, resulting in a horizontal subsurface sampling spacing of 12.5 m.” to read “…hydrophone groups, or traces, at 25 m spacing, resulting in horizontal subsurface sampling at each midpoint between the shot location and hydrophone group of 12.5 m.”

Page 364 line 24 – “temperature”. This is rather bold in view of the following sentence with a significant salinity influence, and Sallarès et al (2009) find up to 40% salinity contribution in places. However, I agree with the sentence in lines 27-29.

The analysis of Sallarès et al (2009) convincingly shows that the contribution of salinity anomaly to reflectivity (on the average) is about 20% but can increase up to 40% if stratification is doubly diffusive. Ruddick et al. (2009)’s results are consistent: at the periphery of a meddy they estimate a contribution of 83% and 17% from thermal and haline anomalies, respectively. They conclude that seismic images are essentially smoothed maps of temperature gradient (hence our wording in the original submission). Acoustic impedance contrasts are associated dominantly, but not entirely, with temperature anomalies. We therefore replace “...seismic imaging is essentially a smoothed vertical derivative of temperature....” with “..seismic imaging is approximately (but not entirely) a smoothed vertical derivative of temperature....”.

Page 367 line 8 – “time-migrated”. Please explain or cite. [This might be the justification for “10 m horizontal resolution”?]

We now give the following explanation on time migration where it first appears on page 365 line 27. And as the reviewer notes, the migration improves the horizontal resolution, which is also clarified in the revised version.

“Ruddick et al. (2009) give an introduction to basic principles regarding the vertical and horizontal resolution associated with seismic sampling, and describe migration and its consequences on the horizontal resolution. The horizontal resolution is expected to be better than the Fresnel zone radius $R=(\lambda h/2)^{1/2}$ where h is the reflection depth and $\lambda = c/f_0$ is the wavelength of sound, c is the sound velocity and f_0 is the wavelet peak frequency (Ruddick et al., 2009; Sheriff and Geldart, 1995). Between 550 and 850 m, covering the depth range of the thermohaline staircase identified in Sect. 3.1, R varies between 110 and 150 m. Migration partially increases the horizontal resolution which lies between R and the hydrophone group spacing.”

Page 367 line 10. “. . (Ai) . .”?

Yes, corrected.

Page 367 lines 16-18. Why not use the optimum from Fortin and Holbrook (2009)?

According to Fortin and Holbrook (2009), the optimal imaging requires *in situ* sound speed profiles. We do not have accompanying CTD measurements during the seismic survey. Therefore we use a representative constant speed of sound and inform the reader about this caveat. No action taken.

Page 367 lines 23-24. This implicitly assumes $\lambda/4 >> 4$ m.

In response to a comment of reviewer 3, we adopt a more conservative vertical resolution of 10 m (see also our reply to reviewer 3's comment on Page 366). Accordingly we apply 10 m vertical bin averaging to the CTD data. In the original version, $\lambda/4$, or the limit of vertical resolution is 4 m based on a calculation detailed in section 2.1, lines 19-26, using the highest recorded signal of 100 Hz measured at the depth of the staircase and an average recorded sound speed of 1491 m/s. At the dominant return frequency of 30 Hz, $\lambda/4$ is about 12.5 m. Scaling the CTD depth sampling down from 0.5 m to 10 m imposes a more realistic vertical sampling rate on the CTD to what the seismic reflection method is capable of detecting, or layers greater than or equal to 10 m. We have amended the text to include a reference to the calculated value in section 2.1.

Page 367 line 25. Scale is not the same as wavelength. 50 m is the wavelength for the dominant frequency 30 Hz, and high pass to retain scales < 50 m seems reasonable, but the juxtaposition of "scale" and "(the wavelength" is confusing.

Agreed. In the revised version we use scale and wavelength properly. This part on high-pass filtering, however, is removed from the text. Our revised calculations do not apply the high-pass filtering, following the comments of the other two reviewers.

Page 368 section 2.3. It is not made clear what "synthetic modelling" means. Acoustic model? 2D? Simulated air-gun source or believed resulting signal?

The text has amended to read "…2D acoustic synthetic modeling of a shot gather using a simulated air gun size, shot and receiver spacing of the actual seismic survey, is conducted.."

Page 368 line 19 expression for N. Better "Rho**-1" than to use "/Rho" here.

Done.

Page 369 line 8. I don't know "superjacent". Also the figures really are not clear enough to see an increase from 19 m to 25 m.

We replaced "superjacent" with "adjacent". Yes, although Fig 2 is of very high quality, the inset is too small to detect an increase of 6 m in thickness. The result follows from detailed analysis of peak-to-peak vertical distance between adjacent wavelets. The information on the thickness of the layers is useful, and we replace "Layer thicknesses, measured as peak to peak distance between superjacent wavelets, increase with depth from about 19 m to 25 m." with "Layer thicknesses, measured as peak to peak distance between adjacent wavelets, vary between 19 m and 25 m." Furthermore we enlarged the inset in Fig.2 and the increase in layer thicknesses is legible.

Page 369 line 11. “. . not an artefact . .”. This is a strong statement! So it ought to be justified by evidence (e.g. nothing like it elsewhere in the image?). I think lines 11 to 14 could be rearranged to make the logical argument stronger.

Reviewer 3 suggested to remove these lines because there is no reason for there to be processing artifacts and this sentence only leads reader to think that there may be one. We revised lines 11-15 as: “...lack of modulations and slope. The stack of regular, uniformly-spaced quasi-horizontal reflections form bands which are not present elsewhere in the section. Here, it is suggested to be representative of the thermohaline staircase.”

Page 369 line 21. “.. necessary for staircase ..” In the Introduction, first paragraph, it was implied that there could be a (convective) staircase with temperature and salinity increasing downwards.

Clarified as “..necessary for salt-finger staircase ...”

Page 370 lines 1-3. There is a problem reconciling these locations and lengths with each other, or with Figure 2 and its caption. 11 is not 212 – 189 (and this is an east-west section). Certainly “the reflective horizons become less regular and have lower amplitudes at ~ 175 km” but in the figure one could say the same at 185 km. This is crucial because of the specific identification that is the essence of the paper.

We thank the reviewer for identifying the inconsistency between the figure and the text. We corrected and also improved our identification of the staircase as follows: “The staircase imaged in the seismic line extends about 22 km eastward from its position in Fig.2 at about 190 km to about 212 km, in the depth range of 550-700 meters. However, reflective horizons become less regular and have lower amplitudes westward of about 200 km with the deepest high gradient layer disappearing altogether in places.”

Page 370 lines 6-12. This is all OK for dT/dz and dS/dz positive (T and S increasing upwards). If dT/dz and dS/dz are negative then R > 1 implies instability. So what about dive 124 near / just below 600 m ?

The CTD profiles show intrusions susceptible to diffusive layering convection. For T and S increasing downward $1/R_\rho > 1$ (not $R_\rho>1$) implies instability, when R_ρ is defined and plotted as in the manuscript. The strongest diffusive layering is expected for $1< 1/R_\rho < 3$. We now clarify this in the revised version. In Figure 4 in addition to R_ρ (shown in the range $1< R_\rho<2.5$) we also include $1/R_\rho$ (shown in the range $1 < 1/R_\rho < 2.5$) that highlights portions strongly unstable for diffusive layering. Figure caption is revised accordingly.

Page 371 line 3. “Fig. 3 of Schmitt et al., 1987” is also cited in section 2.1. Perhaps it should be reproduced in the paper.

Done. Fig 7 is completely revised including a plot of C-SALT tow-yo CTD data.

Page 371 section 3.4. I don’t think this discussion of longevity is very good. Can the staircase be maintained by the salt-fingering process? It could be advected away. Persistence at any one place would seem to be chancy! In particular advection would seem to be likely to cause a lifetime < 3 years at any one location. In the absence of maintenance by salt-fingering, one would expect a lifetime of order (depth scale)**2 / diffusivity, e.g. 10**2/10**-5 seconds ~ a few months.

Fingers have maintained the staircase in this area for many decades, despite advection, eddies and internal waves. Observations of steps from as early as 1969 (Bomex experiment) have been noted. Of course the exact locations and the quality of steps at the edges are subject to variability, but there are always steps present in the area. We improved the discussion on longevity (see also reply to Barry Ruddick's comment 14). We avoid discussing the expected lifetime from diffusivity due to uncertainty and sensitivity to the involved parameters. For example plausible values of 15 m thickness and a diffusivity of 10^{-6} $m^2\ s^{-1}$ yield a life time of over 7 years.

Page 374 lines 17-18. This spectral behaviour should be related also to the true horizontal resolution – depending on the processing? – c.f. comment re page 364 line 15. Line 18. I don't understand "before"; 125 m is where the spectrum flattens.

There is a change in slope in the spectral shape at about 125 m horizontal wavelength. This is more pronounced for the more energetic open ocean samples. The ensemble-averaged spectrum from the less energetic staircase does not flatten out before about 50 m wavelength. Because the spectral level of the open ocean samples is higher, we do not expect noise signature at wavelengths longer than 50 m, and attribute the change in slope to physical processes in response to Aves Ridge and variable local bathymetry. We clarified these points in the revised version. In the revised version we present the displacement slope spectra following the recommendations of the other reviewers. We further emphasize the presence of noise peaked at 50 m wavelength due to shot spacing.

Page 375 lines 26-28. This sentence may be true but it first needs to be made clearer what character of reflection can be interpreted as a thermohaline staircase. [Especially with the confusion at the top of page 370 c.f. figure 2].

Clarified.

Figure 3 caption, line 3, "less" not "lower"; lines 3 and 5 omit "between".

Done.

Figure 9: I do not understand the scales. The last "trace" (does it mean hydrophone group?) is at 4.1 km but the "depth" of the direct arrival there ~ 1.4 km: twice 1.4 is 2.8 not 4.1. Maybe sound speed comes in but not with these scale labels.

We improved Fig.9 and its description. We inserted a horizontal distance axis. The text is amended to define a trace as a hydrophone group in section 2.1. We also included an inset showing the HRP123 profile and the reader can directly associate the synthetic seismic structure with the sound speed structure. Figure 9's caption is clarified to read

"Unstacked synthetic seismic shot gather using the CTD profile from HRP dive 123 east of Line D2 (Fig1). The direct arrival appears as large amplitude linear reflections starting at the sea surface. The airwave appears as the large linear event traveling at low velocity. Reflections from synthetic sound velocity and density structure calculated from the CTD are seen as hyperbolic horizons starting at about 200 m at trace 1, at zero offset, which occurs directly below the source. Reflections from further offsets follow a hyperbolic moveout with respect to the zero offset trace, and are corrected to zero offset before stacking, using the appropriate sound speed to convert from time to depth. Note that only depths at zero offset correspond to depths on a stacked section. The synthetic staircase is imaged as the next strongest coherent packet of four reflections with the same moveout, visible at higher offsets. The insets show (left) a portion of the sound speed and temperature profiles from HRP dive 123 and (right) a blow-up of the synthetic seismic shot gather marked by the rectangle. Red arrows associate the staircase reflections with the measured staircase. Also shown are relatively strong deep reflections associated with the two intrusive features (dashed arrows)"

Reply to Barry Ruddick, Referee #2

This is a very good paper, using a combination of legacy seismic and conventional oceanographic profiler data to directly address oceanographic questions focused on the strong thermohaline staircases near Barbados. The data are not coincident but an intelligent discussion of the effects of non-coincidence ameliorates this issue a great deal. The paper shows that staircase steps are well-imaged, including resolution, source wavelet effects, and with correct amplitude – and it's rare that amplitude is well-calculated in water column seismics. Oceanographic data AND seismic data are used in combination to investigate the internal wave field in the staircase.

My only complaint overall is that the main focus comes across as " we can see the layers and they are consistent with synthetic seismic images". I think the paper would be a lot stronger if the seismic data were used to tell us something NEW about the staircases. I have two suggestions. In figure 2 the staircase is visible from 190-212 km, and has a fascinating tendency to fade in and out. This is a pretty unique finding, it could be used to learn something about how staircases connect to a non-staircase adjacent region. Maybe the spacing or amplitude changes (or doesn't). Maybe there is a subtle shift from negative reflectors to reflectors of both signs (as in intrusions).
Our primary aim in this paper is to show the capability of seismic reflection method to image a thermohaline staircase. Lacking joint oceanographic and seismic sampling, we hesitate to report details on the staircase structure. Particularly the tracking of reflection surfaces when the staircase fades out is difficult and uncertain. We therefore cannot digitize and conduct spectral analysis in these regions.

Secondly, a strong result from the paper is the analysis of internal wave energy levels from reflector displacements, with a good comparison with shear and microstructure observations. It's convincing, but this was discovered previously by conventional means. How about extending the analysis to map the internal wave energy over the whole eastern part of the section? In particular, you could map internal wave energy levels as one moves from the staircase to the region outside the staircase. This would help to test the "chicken/egg hypothesis" about staircases: ***Perhaps staircases filter out the shorter vertical wavelengths of the IW field, which reduces shear and turbulence, and so allows the staircase to be maintained.***
We thank the reviewer for the inspiring ideas and suggestions. As described above, it is not possible at this time to extend the internal wave energy calculations to the portions of the image with very weak reflections. Furthermore the seismic data from this particular survey suffer from noise at 50 m wavelength (discussed in the revised version). We prefer to postpone such a study for purposefully-sampled better-quality seismic data supplemented by joint physical oceanographic measurements. In conclusions, at the end of the second paragraph we inserted: "Whether weak internal waves allow the formation of the staircase, or the double-diffusive convection of the staircase suppresses the internal waves via the mechanism of Ruddick (1985), is not known at this time."

My recommendation is that the paper is strong enough to publish as it stands, but I would love to see the ideas above followed up. I have a number of minor suggestions below that could help with ease of reading, and a few minor science comments sprinkled in. I leave it to the authors to decide how to address them, and don't require a detailed accounting of how they are dealt with.
We hope to undertake a joint physical oceanography and seismic reflection survey which will be most useful to follow up these ideas.

1. Figs 4-9 seem to jump between the three data sets. I suspect that fig 8 is the culprit and could be shifted.

Figures 4-9 follow the structure of the results section. We prefer to retain Fig 8 after Fig 7 because it allows for an immediate comparison with the CTD-derived and seismic-derived reflection coefficients.

2. P367. lines 24-26. So long as R is well-resolved compared with the source wavelet, it shouldn't depend on the source wavelet at all. In particular, high pass filtering to remove content longer than 50 m shouldn't be needed, or even used. The act of convolution with the source wavelet takes care of all of that.
We agree with the reviewer. In the revised version of Figure 7, we used 10-m bin-averaged profiles without high-pass filtering. 10-m vertical averaging follows from a more conservative estimate (instead of 4 m) of the vertical resolution, following reviewer 3.

3. P 370 lines 14-16. Statement beginning :Although the density ratio...". Figures 4 and 5 don't really prove this statement to me. Can the figures be improved to bring this out? Idea is to show that the shear and not the density ratio account for the non-existence of staircases. Perhaps superimposing a smoothed density ratio field and shearˆ2 field as contours or color shading.
We improved the second panel of Fig 4 to bring this point out. We use different markers, with increasing size, to show the enhanced (10 m) shear portions of the profiles. Figure caption is revised accordingly.

4. Also, figures 4 and 5 could be made to match the geography of the profile locations if they were plotted with 128 on the left.
Done.

5. Figure 4b. You apparently masked 0<R<1, which is relevant to diffusive sense convection and therefore staircases vs intrusions, and definitely exists in some of the profiles. Probably best to put it in.
In the revised Figure 4b we also include $1 < 1/R_\rho < 2.5$ that highlights portions strongly unstable for diffusive layering. Figure caption is revised accordingly. See also reply to reviewer 1's comment on p.370, lines 6-12.

6. Fig 5 caption. The "(i.e., every 10th data point)" is confusing unless you state delta-z = 0.5m.
Clarified by revising as: "(i.e., every 10th data point of 0.5 m vertically sampled profiles)".

7. Fig 7 really should be augmented with a second panel that shows the result of convolving R with the source wavelet, and somehow showing the source wavelet, likely showing how negative apparent reflections are generated by the wavelet sidelobes.
Fig 7 is completely revised. It now includes a waterfall plot of C-SALT temperature profiles followed by a distance-depth map of inferred reflectivity.

8. The calculated R (fig 7) is pretty much completely negative, but there are strong positive reflection bands in the seismic image of figure 2 inset. And the reflection coefficient in fig 8 appear to be both positive and negative, if I read the figure correctly. This is all pretty confusing - can you change the text to clarify?
Figure 7 is completely revised. The depth-distance map of inferred reflectivity shows equally strong positive and negative peaks. Figure 8 (reproduced at higher quality using a new colormap and masking the erroneously high values) also shows equally strong positive and negative peaks.

9. Fig 8 caption "100 and 400 m" Do you mean 1400 and 4000 m?
Corrected (from 1000 and 4000 m to 1400 and 4000 m).

10. Fig 9. Axis should include offset in km. And you have an opportunity here to point out the usefulness of the streamer, with non-vertical reflections, since the figure clearly shows larger amplitude at non-zero offset.
Done.

11. P371, line 20. "Changes" is unclear - maybe use "vertical contrasts"?
Done.

12. P 372, top of page (lines 1-3). You use CTD info to calculate a synthetic, and then compare reflector depths to CTD-derived depths? Hmm......
Yes, the data are not independent. However, in this analysis our aim is to show that the sound speed contrasts associated with the thermohaline staircase can be imaged by seismic reflection method. By mimicking the actual sampling and processing procedure in an ocean with the given CTD profile, we successfully obtain reflectors that delineate the staircase.

13. Fig 10. If the point is to compare Eps_obs and Eps_IW, why not show them in the same panel, with stn 127 on the left?
Done.

14. Section 3.4 on Longevity of staircase. There must be some useful CTD info in the usual databases to better address this.
At Section 3.2, at the end of the second paragraph, we inserted: "Thermohaline staircases have been observed many times in the area east of the Caribbean Sea since the early days of continuous electronic profiling, including STD profiles from 1967 (Mazeika, 1974)."
At the end of Section 3.4, we inserted: "Thus, the staircase had a lifetime of less than 3 years at this particular site. However, since this location is at the boundary of the strong staircase region identified during C-SALT (Schmitt et al, 1987), it seems most likely that the steps have simply retreated from this spot due to the varying ocean currents. It is believed that a staircase can always be found in the thermocline east of the Caribbean, since the strong vertical salinity gradients are maintained by the advection of both the salinity maximum water and salinity minimum water into the region by the general circulation."

15. It's more common (?) to show and use slope spectra, and is easier to justify for seismic reflectors since you don't have absolute knowledge that the reflectors follow isopycnals on all scales. If you don't do this, you should at least mention the kˆ2 link to slope.
Agreed. In the revised version we present the slope spectra.

16. P 374 line 6. "Spectral" seems like a change of subject and might have a paragraph break to indicate this.
Done.

17. P 374 Top few lines. "Another conclusion...". How can this conclusion come from figure 10? Perhaps you should tell us Nˆ2 or (N/N_o)ˆ2 in the caption, and/or show a dashed line in the figure corresponding to the 0.6 value.
Thanks for pointing this out. Because Fig.10 is very crowded, we simply report the average $\langle S_{10}^4 / S_{GM}^4 \rangle$ in the staircase. We revised this part as:
"The ε_{IW} profile of dive 123 also shows that the internal wave field is significantly less energetic than the GM field. When averaged in the depth range of well-defined steps, $\langle S_{10}^4 / S_{GM}^4 \rangle$ is about 0.8. This is in agreement with Gregg (1989) who found $\langle S_{10}^4 / S_{GM}^4 \rangle$ of about 0.6 for the C-SALT staircase."

18, "reflector" and "reflection" seem to be used interchangeably, but the reflector is the thing that causes the reflection that is seen in the image.
Corrected throughout.

Reply to K. Sheen, Referee #3

This manuscript demonstrates the utility of seismic oceanography in providing new insights into the spatial distribution of thermohaline finestructure and internal wave energy. Such insights are particularly useful considering the coarse horizontal resolutions of more traditional oceanographic techniques and subsequent lack, for example, of observed horizontal energy spectra. By the thorough analysis of independent regional measurements, the manuscript clearly shows (by qualitative examples) that a thermohaline staircase has been seismically imaged, and is associated with low internal wave energies. However, I feel that the novelty of the manuscript is compromised by the absence of a detailed qualitative description of the imaged thermohaline staircase, and a lack of quantitative comparison between seismic and oceanographic data.
In the revised version we have improved the qualitative description of the imaged staircase (see reply to more specific comments below and to those by B. Ruddick) . We have avoided detailed quantitative comparisons between seismic and oceanographic data, because they are sampled in different years. The aim of the paper is to demonstrate, with the data at hand, the ability of seismic reflection method to image staircases. To use the seismic reflection method to improve our understanding of staircases is the next step, but it is beyond the scope of this study.

The main contribution of seismic reflection profiling to oceanographic observations is its ability to image thermohaline features at unprecedented horizontal resolutions. A discussion (and better image) of the horizontal amplitude variation within the staircase reflectors, particularly where they diminishes at the staircase western edge would have been interesting (as suggested by reviewer 2). Moreover, the whole seismic section shows some spectacular structures, which are not interpreted or even mentioned in the manuscript.
It is not the aim of the paper to address and discuss these spectacular structures. There is neither room nor supporting data to discuss these features in detail. The diminishing western edge of the staircase is discussed in response to B. Ruddick's comment. Seismic reflection method has been shown to image many spectacular oceanographic phenomena which are reported in detail in the recent literature, as outlined in the introduction.

I am unconvinced by the reflection coefficients computed from the seismic data. No errors are given, but the coefficient values do not match particularly well to those of the C-SALT CTD. Moreover, I suspect that the other CTD data used in the manuscript is likely to show even smaller reflection coefficients, and thus be even less correlated to the seismically deduced values. Why do the reflectivity coefficients change so much across the staircase section in regions where the stacked image amplitudes appear more or less continuous? Please see later comments.
I am unsure that the synthetic shot gather contributes to the manuscript. Other than the influence of the direct wave, the same conclusions could be achieved from computing a zero-offset seismogram from the CTD data (i.e. convolving the reflectivity as computed from the hydrographic data, with the seismic source wavelet). No attempt is made to look at amplitude variation with offset, incorporate background noise or input a background velocity field, which spatially varies over the streamer length. Such synthetic modeling from hydrographic data is not novel. Displaying a shot gather without giving any background about the seismic reflection profiling experiment makes the synthetic modeling section inaccessible to readers not familiar with the technique. The results of the synthetic analysis are not displayed clearly, or in a manner which can be easily compared to the observed stacked seismic section.
We concur, yet maintain that a synthetic experiment to provide an image using the same setup as the actual seismic survey, rather than a zero-offset seismogram, is helpful, though certainly not novel, to show that acquisition parameters were sufficient to capture the

presence of a staircase. We amend the figure caption (also per Reviewer #1) to explain the importance of observing the hyperbolic move-out of the indicated staircase reflectors on the shot gather and give more background to what the image shows. Amplitude variation with offset would be a natural extension of these results, but would require extensive analysis and processing beyond the scope of this study. We did not make an attempt to model background noise as it was reduced by stacking post-migration. Decimation studies and an investigation of the effect of noise would be an interesting extension, yet not the purpose of this paper.

The authors claim that the data gives insight into the longevity of thermohaline staircases. However, no evidence is given as to how long the staircase was present before the seismic data was shot. I would recommend cutting this analysis completely and simply adding a sentence referring to the typical lifetimes (several months) of such features as found from previous studies.
We retain and further improve the discussion on the longevity of thermohaline staircases.

The data is novel, as far as I am aware, in showing a towed displacement spectra of a thermohaline staircase. However, with such a wealth of proximal current and microstructure measurement available for comparison, it seems a shame that the spectral analysis of seismic displacement spectra was not more quantitative. It would be good to compute dissipation rates from the seismic spectra (e.g. see Klymak and Moum (2007), Sheen et al., (2009)). Best-fit slope estimates at different wavelength regimes would also add some insights. It would also be nice to see internal wave energies (or at least spectral amplitude) mapped across the whole section. See later comments.
The discussion of the spectra is improved in the revised version (section 3.5 is largely re-written and is not reproduced here). We now present slope spectra and also discuss the turbulence subrange. In the revised version, we quantify the slopes in different ranges. In our data set, the slope spectra from the reflections are contaminated by noise at high wavenumbers, dominated by the peak at 50 m wavelength due to shot spacing. Our spectra cannot be interpreted in terms of turbulence subrange and this is beyond the scope of our paper. We clarified these points in our discussion in section 3.5. We do not attempt to compare best-fit dissipation rates from the turbulence range of the slope spectrum with non-concurrent dissipation measurements. The data is not suitable for such a study and requires dedicated and joint sampling. Next, unfortunately, the internal wave energies cannot be mapped throughout the whole section due to portions of the section transparent to sound.

Overall, I recommend publication but after improvement to figure clarity, robustness of reflection coefficient estimates and perhaps more in depth analysis of the data. Some more detailed comments follow.
We thank the reviewer for the comments and suggestions. We improved our methods, analysis and figure quality.

Figures:
Fig 2 - Mark HRP locations on axes. It would be better to see the staircase inset enlarged in a separate figure, as this feature is the focus of the whole paper. I would also include a larger region, to encompass the fading out of staircase reflectors at depth and on the western edge. Reflector separations could be clearly marked, showing their 20 m separation and increasing thickness with depth.
We improved Figure 2. We marked the location of HRP casts, and enlarged the size of the inset.

Fig 7 - Can you include the temperature and salinity profiles here? In addition a plot of the reflection coefficients convolved with a source wavelet would enable easier comparison to

seismic data, and demonstrate more robustly that the seismic data is able to resolve the staircase layers. In addition, not accounting for the source wavelet means that positive reflection coefficients are ‘missing’, making it difficult to compare to Fig 8. Alternatively plot the reflectivity depth profile computed from the seismic image, de-convolved from the source signature. It would also be useful to plot the reflectivity profile of HRP station 123, which is used for the synthetic modeling and is more proximal.
Fig 7 is completely revised. It now includes waterfall plots of temperature profiles and distance-depth map of inferred reflectivity.

Fig 8 – Plot is not very clear. Perhaps show the inset from Figure 1 alongside this Figure for easier comparison. The caption here indicates that the higher reflectivity is erroneous - can we really trust these values? I think that the normalization value, A_0 should be constant throughout the seismic transect. Perhaps it would be better to compute the normalization value averaged over one or two a horizontally layered sections, which show a clear multiple and seabed reflection and use the same value throughout the data. You could plot a depth profile of the reflection coefficients on Figure 7.
Because the amplitudes of the reflectors through the water column are very small, it is possible that they could be obscured by cdp-specific anomalies such as the noise bursts evident in Figure 8, which is the reason for the normalization in the first place. But if an average A_0 is used, these trace-specific modulations would not be adequately addressed by an average A_0, or possibly even it’s neighboring trace’s A_0. It may be possible to remove or obscure this noise with post-migration noise attenuation processing or perhaps by using different velocities or migration algorithm. However, seismic data is routinely interpreted in the presence of this kind of noise, and its fidelity measured by the presence of laterally coherent reflectors.

Fig 9 - Confusing for readers not familiar with marine seismic data acquisition and processing. What is the strong linear feature, which comes in at times later than the direct arrival? It is very difficult to compare the model to the CTD data or seismic section. Why plot the whole shot gather, when the region of interest is too small to see clearly? Plot the inset bigger so that reflector depth variations can been seen. What are the brighter hyperbolic reflections at 850 m depth? How is depth computed from two-way-travel-time? Perhaps perform a normal move-out correction and overlay a modeled stacked seismic trace in Fig 2/Fig 6. Offset (km) should be added to the axes.
Figure 9 is revised to include the offset (km) and an inset showing the measured temperature and sound speed profiles. Seismic signature is matched with the measured profile with arrows to guide the reader. Brighter deeper reflections are due to the intrusive features marked by the dashed arrows. The region of interest has been enlarged with an explicit reference to hyperbolic moveout of the reflectors in the figure caption. Depth is computed using the measured sound speed. The figure caption is amended to explain the reflectors more clearly.

Fig 11 - Please give a clearer indication of the regions over which the reflectors were tracked. It is better to de-trend the spectra by multiplying by kˆ2 (or kˆ(2.5)), otherwise it is vey difficult to compare slopes with the GM spectra. You should reference Krahmann et al., 2008, for justification of the assumption that every 6th reflector is de-correlated.
In the revised version, we present the slope spectra (i.e., displacement spectra times $(2\pi k_x)^2$, where k_x is the horizontal wavenumber). This allows an easier comparison with GM as well as turbulence-subrange curves. A reference to Krahmann et al. (2008) is inserted.

Text:
Page 362, line 9: Clarify ’background levels’. Does this refer to other regions of seismic image or the noise level?

Amended to read ‘background noise’.

Page 362, line 19: Not sure it can ’improve estimates’. Seismically deduced dissipation rates have large uncertainties and no attempt is made here to extract quantitative values of mixing from the seismic data. Seismic techniques can certainly add to mixing estimates (particularly from horizontal spectra) and give a better indication of the spatial variation of ocean mixing.
In the closing sentence of our abstract we are pointing out the potential for seismic methods to contribute to an improved understanding of occurrence rates and the geographical distribution of staircases. The mixing ascribable to salt fingering, in the bulk sense, will follow from this information. We made minor changes in the abstract to clarify this point. The method to estimate mixing from horizontal wavenumber spectra that the reviewer has on mind is another issue. While the method is promising to infer maps of diapycnal mixing in the water column, it bears large uncertainties for double diffusive mixing processes, e.g., the assumption of 17% mixing efficiency in the Osborn model.

Page 364, line 16: Remove ’full’
Done.

Page 364, line 25: I don’t see how this contribution of temperature to reflectivity is shown in section 2.2.
This is now clarified. The reference to section 2.2 was for the definition of reflectivity, not for the contribution of temperature contrast to reflectivity. We moved the cross reference to Sect.2.2 to the end of the sentence, and revised as “..see Sect 2.2 for definition of reflectivity)”.

Page 365, lines 8-9: Double-diffusive thermohaline staircases are density compensating, as demonstrated in lines 22-25, p370. It follows that staircase seismic reflectors, which largely follow temperature gradients, do not necessarily track isopycnals. Please check vertical density gradients against that of temperature or acoustic impedance.
Thanks for pointing this out. We caveat this, in the revised version, later in Sect. 2.4, by inserting “. This analysis assumes that the reflection horizons oscillate with the isopycnals, which can be erroneous in the presence of density-compensating thermohaline staircase and intrusions”. Page 365, where we are outlining the structure of the paper at the end of introduction, is not the right place to introduce this discussion.

Page 365, lines 25-27: Was the direct wave addressed at all in processing? Figure 9 indicates that the direct wave may affect reflectivity up to 400 m depth, very close to the thermohaline staircase. To clarify to readers not familiar with seismic techniques, add a sentence explaining the reason for Kirchoff migration, and also why time-migration is used for reflectivity computations.
The direct arrival was muted during processing of the seismic data. The text is amended to note this. The text has been amended to explain the effect of migration on horizontal resolution in response also to a comment from Reviewer #1. The reasons for time migration are added as well: “... Lastly, data were input into a 2D Kirchhoff migration, an algorithm chosen for simplicity and ease of calculation in time rather than depth, as no highly varying lateral velocity variations were expected to be encountered in the water column.”

Page 366, lines 23-26: Widess, 1973, state a vertical resolution of one eighth the DOMINANT wavelength. For the dominant source frequency here (30 Hz) this gives a resolution limit of > 6 m. In addition, the Widess criterion is for a single, isolated, high velocity layer in a homogeneous background. Here we have a series of steps, temperature changes are smoother in water compared to rock layer interfaces and there are effects such as interleaving. Please be more conservative than 4 m.

Agreed. Revised as: “For a single isolated rock-layer interface in a homogeneous background, the vertical resolution is 1/8th of the dominant wavelength, in this case about 6 m (Widess, 1973). The vertical resolution is expected to be coarser due to presence of a series of steps and smoother acoustic impedance contrasts in water compared to rock layer interfaces. Thus, the seismic reflection method should be able to distinguish layers as thin as 10 m.”

Page 367, lines 7-9: Later you say that the typical acoustic velocity is 1491 m/s?
Recalculated using 1491 m/s.

Page 367, line 14: What do you mean ’moved up’. Mixing of time (earlied/later) with geology (up/down).
Text amended to read ‘moved’.

Page 367, line 24: Why use a high-pass filter? It would be better to convolve the reflectivity series with a wavelet similar to source wavelet.
In the revised calculations we do not use high-pass filter and use a quantization interval of 10-m. We obtain and discuss the reflectivity (by the convolution of impedance with the first difference operator). The convolution of the reflectivity with the source wavelet would give the seismogram, which we do not introduce in the paper.

Page 368, section 2.3: Explain in more detail what you are modeling i.e. shot gather, the source frequency content, techniques used (finite difference?)
The text was amended per comments from Reviewer #1 and further to read ‘…modeling of a shot gather, using…’

Page 369, lines 11-12: ’sampling’ - well it is affected by the source wavelet frequency content. I would omit lines 11 and 12. There is no reason for there to be processing artifacts and this sentence only leads reader to think that there may be one!
Done.

Page 370, lines 1-3: These lengths don’t match up (212 km -189 km is not equal to 11 km)
We apologize for these errors. These are corrected in response to reviewer 1.

Page 373, lines 18-20: Station 127 does show higher dissipation rates but it is also much closer to the continental shelf, than the staircase CTD (123). Would it not be better to compare station 123 with say 125
This is another good point. We inserted a new panel for the HRP dive 126 which indeed shows less turbulence. The text is revised accordingly to include fine-scale parameterization and observation comparison for dive 126 as well.

Page 374, lines 14-15: Klymak and Moum (2007) show that in general it would be surprising to find a kˆ(-2) horizontal spectra in the open ocean. They show that the vertical spectra roll off at 10 m in a GM wavefield, affects the horizontal spectra, depending on the frequency content of the wave field. A -2 slope is not generally observed and that is why Garrett and Munk fit a -2.5 spectra in 1975.
Agreed. We now use GM75 which has -2.5 slope at high wavenumbers and approaches -2 slope at low wavenumbers..We use the displacement slope spectra (hence the slopes become -0.5 and zero). We also point out that our slope spectra are consistent with the -0.5

slope suggested as a good model for the entire internal wave range by Klymak and Moum (2007).

Page 374, lines 16-27: The staircase spectra appears to exhibit a steeper slope in the internal wave regime than the open ocean spectra. Can you compute the mean slopes at different wavelength regimes? What are the kinks at wavenumbers around 10ˆ(-2.3) cpm and 10ˆ(-1.9) cpm, which are observed in both the open ocean and staircase?
We now quantify and discuss the slopes on the spectra.

The first kink may represent the transition to the stratified turbulent regime (Klymak and Moum (2007), Riley and Lindborg (2008)). The fact that the first change in spectral slope occurs at lower wavenumbers in the staircase spectra compared to spectra from the 'open ocean', adds to evidence for lower internal wave energies in the staircase. Perhaps the second kink is the influence of noise, but then I would expect all spectra to reach the same level.
We added detailed discussion on the spectral behavior in the revised version. In our data set, the slope spectra are contaminated by noise at high wavenumbers, dominated by the peak at 50 m wavelength due to shot spacing. We cannot interpret our spectra in terms of turbulence subrange. According to the study of Klymak and Moum, the transition from the internal wave range to the turbulence range is shifted to lower wavenumbers for increasing levels of turbulence. Given that the turbulence level out of the staircase is higher, the first change in spectral slope in the staircase spectrum is inconsistent with Klymak and Moum.

Page 374, lines 25–26: Are you sure that the drop-of above the 1 km scale is not a spurious data point at the end frequency, due to averaging over the whole tracked line?
The first spectral data point is not a spurious data point, but it depends on the method of calculating the vertical displacements. Consistent with other work, we linearly detrend segments of digitized reflections. Alternatively one can remove the mean from the segment, which change the first spectral point. We choose removing the linear trend because steeply tilted reflection surfaces would lead to spurious vertical displacements when only mean is removed.

-------------- END OF REPLY TO INTERACTIVE COMMENTS -------------------

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Seismic imaging of a thermohaline staircase in the western tropical North Atlantic

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Abstract. Multichannel seismic data acquired in the Lesser Antilles in the western tropical North Atlantic indicate that the seismic reflection method has imaged an oceanic thermohaline staircase. Synthetic acoustic modeling using measured density and sound speed profiles corroborates inferences from the seismic data. In a small portion of the seismic image, laterally coherent, uniform layers are present at depths ranging from 550–700 m and have a separation of ~ 20 m, with thicknesses increasing with depth. The reflection coefficient, a measure of the acoustic impedance contrasts across these reflective interfaces is one order of magnitude greater than background noise. Hydrography sampled in previous surveys suggests that the layers are a permanent feature of the region. Spectral analysis of layer horizons in the thermohaline staircase indicates that internal wave activity is anomalously low, suggesting weak internal wave-induced turbulence. Results from two independent measurements, the application of a finescale parameterization to observed high-resolution velocity profiles and direct measurements of turbulent dissipation rate, confirm these low levels of turbulence. The lack of internal wave-induced turbulence may allow for the maintenance of the staircase or may be due to suppression by the double-diffusive convection within the staircase. Our observations show the potential for seismic oceanography to contribute to an improved understanding of occurrence rates and the geographical distribution of thermohaline staircases, and should thereby improve estimates of vertical mixing rates ascribable to salt fingering in the global ocean.

1 Introduction

Thermohaline staircases are regular, well-defined step-like variations in vertical profiles of temperature and salinity that can occur when vertical temperature and salinity gradients share the same sign

(Kelley, 1984). In the ocean, they are the result of double diffusion driven by the difference in molecular diffusivities for heat and salt (Turner, 1973). In a statically stable setting, density-compensating profiles of temperature and salinity can lead to double-diffusive convection for a top-heavy temperature profile (e.g., typical above the subsurface warm Atlantic Water in the Arctic Ocean, Kelley et al., 2003), and to salt fingers for a top-heavy salinity profile (Stern, 1960; Schmitt, 2003). Double diffusion is shown to influence the efficiency of diapycnal mixing (across density surfaces), for both diffusive convection (Sundfjord et al., 2007) and salt fingering (St. Laurent and Schmitt, 1999) regimes. Here, we discuss the situation where both salinity and temperature decrease with depth, i.e. when a warmer salty body of water overlies a colder fresher body typical for example in the subtropical ocean, leaving conditions favorable for the development of salt finger staircases. Finger instabilities cause small-scale convection cells that can induce significant vertical fluxes at high-gradient interfaces between well-mixed layers with contrasting temperature and salinity.

Studies have suggested that salt fingering can greatly affect the vertical transport of heat and salt in the thermocline and play a significant role in maintaining the global thermohaline stratification (Schmitt et al., 1987, 2005). Salt fingering may play a role in the tightness and shape of the mean temperature-salinity relation in the central waters of subtropical gyres (Schmitt, 1981, 1990). Numerical modeling by Zhang and Schmitt (2000) shows that the stability of thermohaline circulation is highly dependent on a critical freshwater flux value, which is reduced in the presence of salt fingering. Results of the North Atlantic Tracer Release Experiment, conducted near the Canary Islands, indicated an enhancement of saline diffusivity over thermal diffusivity of more than 60% by salt fingering. The mixing rates inferred from tracer dissipation measurements were better explained with the presence of salt fingering (St. Laurent and Schmitt, 1999). More recently, the Salt Finger Tracer Release Experiment (SFTRE) revealed that vertical mixing was greatly enhanced by the presence of a salt fingering thermohaline staircase with a factor of two enhancement of the haline mixing rate over the thermal mixing rate (Schmitt et al., 2005).

The importance of salt finger processes to ocean structure and circulation emphasizes the need to understand their temporal and spatial occurrence in the environment. The application of models, tracer experiments, and laboratory studies to the open ocean is still poorly understood, and further insights can be gained from improving observational capabilities. Our study utilizes geophysical techniques to observe physical processes over a large spatial area in the ocean, which has the potential to add significantly to the body of staircase observations available to the oceanographic community.

New research in marine geophysics has demonstrated the ability of the multichannel seismic reflection method, sensitive to abrupt vertical changes in sound speed and density, to provide images of physical oceanic processes with exceptional horizontal resolution. Holbrook et al. (2003) first related water-column reflections to oceanic finestructure in a front between the Labrador Current and the North Atlantic Current. A descriptive introduction on the seismic reflection method with a focus on water column interpretations can be found in Fer and Holbrook (2008), Ruddick et al. (2009), and Pinheiro et al. (2010). Temperature-salinity contrasts in the water column result in small changes in sound speed and appear in seismic images as distinct reflection layers revealing exceptional detail between 10 - 100 m horizontal resolution throughout the water column. Spectacular images of thermohaline finestructure in the ocean include features such as intrusions (Holbrook et al., 2003), fronts (Holbrook et al., 2003; Nakamura et al., 2006), water mass boundaries (Nandi et al., 2004), internal waves (Holbrook and Fer, 2005; Krahmann et al., 2008), internal tide characteristics (Holbrook et al., 2009) and mesoscale eddies (Biescas et al., 2008; Pinheiro et al., 2010). A clear relationship has been established between recorded seismic reflectance and the presence of thermohaline finestructure (Nandi et al., 2004). A detailed derivation in Ruddick et al. (2009) shows that seismic imaging is approximately (but not entirely) a smoothed vertical derivative of temperature on the scale of the acoustic wavelet (order of 10 m). On average, 80% of the reflectivity is due to temperature contrasts (Sallarès et al., 2009), whereas the typical contribution of salinity anomalies to reflectivity is about 20% (Sallarès et al., 2009; Ruddick et al., 2009) (see Sect. 2.2 for the definition of reflectivity). The latter does not affect the patterns on the final seismic image, since the vertical gradients of salinity and temperature are tightly correlated.

Here, we present a seismic transect from an area previously shown to be prone to salt-finger staircase development, in the western tropical North Atlantic near the Lesser Antilles (Schmitt et al., 1987). Seismic data are supplemented by oceanographic measurements of hydrography, currents and microstructure, and synthetic modelling. Data and methodology are presented in Sect. 2. In Sect. 3.2, we demonstrate the enhanced reflectivity associated with the thermohaline staircase. By modeling a synthetic seismic response to physical parameters, we show that seismic reflections can provide a high-resolution image of a thermohaline staircase (Sect. 3.3). Assuming that the reflectors oscillate with isopycnals, we infer the internal wave field from spectral analysis of seismic data, to show weak internal wave activity in the staircase and provide support from oceanographic measurements (Sect. 3.5). Subsequently, we put a constraint on the longevity of the staircase observed in an earlier hydrography survey (Sect. 3.4). Results from independent sampling and analysis are self-consistent and provide evidence that seismic oceanography is capable of detecting the structure and distribution of thermohaline staircases. The seismic reflection methodology may be used to analyze processes that affect thermohaline finestructure and provide new observational insights into physical oceanography.

2 Experimental methods

2.1 Data

The seismic data were acquired on board the R/V *Maurice Ewing* from 15 March through 6 April 1998 (Bangs, 1998). An air-gun array composed of 20 air-guns with a combined volume of 8420 cubic inches (~ 138 l) generated acoustic energy with shot intervals of 50 m. Reflected energy was recorded on a 4.1-km-long streamer containing 164 hydrophone groups, or traces, at 25 m spacing, resulting in horizontal subsurface sampling at each midpoint between the shot location and hydrophone group of 12.5 m. Data processing follows standard routines including muting of the direct arrival. Data were digitized at 250 samples per second, stacked, corrected for spherical divergence and filtered through a minimum-phase trapezoidal band pass filter. Lastly, data were input into a 2D Kirchhoff migration, an algorithm chosen for simplicity and ease of calculation in time rather than depth, as no highly varying lateral velocity variations were expected to be encountered in the water column. Ruddick et al. (2009) give an introduction to basic principles regarding the vertical and horizontal resolution associated with seismic sampling, and describe migration and its consequences on the horizontal resolution. The horizontal resolution is expected to be better than the Fresnel zone radius $R = (\lambda h/2)^{1/2}$ where h is the reflection depth and $\lambda = c/f_0$ is the wavelength of sound, c is the sound velocity and f_0 is the wavelet peak frequency (Ruddick et al., 2009; Sheriff and Geldart, 1995). Between 550 and 850 m, covering the depth range of the thermohaline staircase identified in Sect. 3.1, R varies between 110 and 150 m. Migration partially increases the horizontal resolution which lies between R and the hydrophone group spacing.

In this study, we present results from Line D2, which was acquired from west to east just outside the Caribbean Sea (Fig. 1). Close to the seismic line, full-depth profiles of conductivity, temperature, depth (CTD), and currents were collected using the High Resolution Profiler (HRP, Schmitt et al., 1988), during the Salt Finger Tracer Release Experiment – Part 2 (SFTRE-2) cruise on board the R/V *Seward Johnson* between 29 October and 4 December 2001 (Fig. 1, stars). The physical oceanography sampling is thus more than three years after the seismic transect. HRP is a free-fall profiler sampling finestructure (CTD and horizontal current) at 10 Hz and microstructure (temperature, conductivity and shear) at 200 Hz, at a nominal descent rate of 0.6 m s^{-1}. Data processing follows standard routines and can be found, for example, in Polzin and Montgomery (1998). Here, 0.5 m vertical resolution profiles of finescale CTD and horizontal velocity, and dissipation rate of turbulent kinetic energy are used. The location of Line D2 and the HRP stations is within the limits of the aircraft-deployed expendable bathythermograph survey of the Caribbean-Sheets And Layers Transects (C-SALT) experiment (Schmitt et al., 1987), and lies approximately 220 km north of the C-SALT CTD tow-yo section. The C-SALT survey was conducted in 1985. In order to calculate the reflection coefficients in a well-defined strong thermohaline staircase, we make use of a C-SALT CTD tow-yo profile (Fig. 7a).

The seismic reflection data from the area at the depths of the staircase indicate a dominant return frequency of about 30 Hz (or a wavelength of approximately 50 m), with a spectral content of 5 to 100 Hz. A CTD profile from HRP indicates an average sound speed of 1491 m s^{-1} between 550 and 850 m (covering the depth range of the thermohaline staircase identified in Sect. 3.1). For a single isolated rock-layer interface in a homogeneous background, the vertical resolution is 1/8th of the dominant wavelength, in this case about 6 m (Widess, 1973). The vertical resolution is expected to be coarser due to presence of a series of steps and smoother acoustic impedance contrasts in water compared to rock layer interfaces. Thus, the seismic reflection method should be able to distinguish layers as thin as 10 m.

2.2 Reflectivity

Acoustic impedance, I, is the product of density ρ, and sound speed, c; both typically vary with depth in the ocean: $I(z) = \rho(z)c(z)$. The reflection coefficient or reflectivity, R_i, is a measure of the impedance contrast at boundaries. See Ruddick et al. (2009) and Sallarès et al. (2009) for a detailed discussion on the relative contribution of temperature and salinity on reflectivity in seawater. In Sect. 3.2 we contrast reflectivity derived from hydrographic observations and seismic data. For the latter, reflection coefficients were derived from a time-migrated seismic profile using a constant sound speed of 1491 m s^{-1}. The amplitude of the sea floor (A_{sf}) and its first multiple (A_{mult}) were used to normalize the amplitudes of the reflections in the staircase (A_i) using $R_i = A_i/A_0$, where $A_0 = -(A_{\mathrm{sf}}^2)/A_{\mathrm{mult}}$ (Warner, 1990). Diffractions at the sea floor underneath the staircase reported incorrect amplitudes and travel times for the reflectors, necessitating the inclusion of time-migration as an additional processing step. After migration, the sea floor was moved into a more consistent position with respect to its location on adjacent common depth profiles, and sea floor amplitudes had less interference from other reflectors. The choice of constant sound speed, however, leads to a reduction in signal-to-noise ratio and can mask features revealed by using in-situ sound speed profiles (Fortin and Holbrook, 2009).

From these data, reflection coefficients were calculated using CTD tow-yo data collected during the C-SALT survey in 1985. For continuous profiles of $\rho(z)$ and $c(z)$, the water column can be approximated as a sequence of layers allowing the calculation of the reflectivity coefficient between two adjacent layers i and $i+1$ as $R_i = (I_i - I_{i+1})/(I_i + I_{i+1})$. Consistent with the seismic profiling vertical resolution of 10 m (a conservative estimate, see Sect. 2.1), a vertical quantization interval of 10 m was applied.

2.3 Synthetic modeling

Using a CTD profile from HRP, 2D acoustic synthetic modeling of a shot gather using a simulated air gun size, shot and receiver spacing of the actual seismic survey is conducted to characterize the pattern of reflectivity expected from finestructure in a thermohaline staircase. Density and sound speed profiles between 10 and 1474 m depth were averaged over 4 m intervals to create a 364 layer representation of the water column. The measured sound speed profile is used to convert from time to depth. The final model used 164 receivers and a streamer length of 4.1 km to match the seismic data sampling (Sect. 2.1).

2.4 Spectral analysis

Vertical displacements of reflections from oceanic finestructure recorded in the Norwegian Sea were shown to be representative of the internal wave field (Holbrook and Fer, 2005). In order to infer the internal wave energy level from spectral analysis, we digitized representative reflection horizons at 12.5 m horizontal resolution, and categorized them into groups based on their proximity to the staircase. Reflection depths were linearly detrended to produce vertical displacements (ζ) from the mean reflection position. Horizontal wavenumber spectra ($\phi_\zeta(k_x)$) were then calculated with a Welch Fourier transform using 128 point long (1600 m) Hanning windows. The spectral analysis assumes that the reflection horizons oscillate with the isopycnals, which can be erroneous in the presence of density-compensating thermohaline staircase and intrusions. Following Klymak and Moum (2007) we present the spectra for the horizontal gradient of vertical displacements, i.e. slope spectra, $\phi_{\zeta_x} = (2\pi k_x)^2 \phi_\zeta$. The slope spectra is suitable for seismic reflection surfaces which do not necessarily follow isopycnals on all scales and also allows an easier visual identification of internal wave and turbulence sub-range. The resulting spectra were scaled by N/N_0 where N is the mean buoyancy frequency within the depth span of the selected reflection and $N_0 = 5.2 \times 10^{-3}\,\mathrm{s}^{-1}$. The buoyancy frequency is approximated from the potential density anomaly σ_θ (referenced to zero surface pressure) as $N = \left[-g\rho^{-1}\partial\sigma_\theta/\partial z\right]^{1/2}$ where z is depth, g is gravitational acceleration and ρ is the reference seawater density. A survey-averaged N profile is calculated over 30 m vertical scale using the CTD profiles from HRP dives shown in Fig. 1.

3 Results and discussion

3.1 Thermohaline staircase

In the spring of 1998, the seismic Line D2 in the Lesser Antilles (Fig. 1) captured patterns suggestive of a salt finger thermohaline staircase (Fig. 2). At least 4 km in length, the staircase is composed of four thick, regular, nearly horizontal reflectors with a vertical spacing of about 20 m, consistent with the structure expected from high-gradient interfaces separating mixed layers. Layer thicknesses, measured as peak to peak distance between adjacent wavelets vary between 19 m and 25 m. This structure located about 190 km east of Guadeloupe visible at depths between 550 and 700 m, is distinguished by its clarity, strong amplitude, lack of modulations and slope. The stack of regular, uniformly-spaced quasi-horizontal reflections form bands which are not present elsewhere in the section. Here, it is suggested to be representative of the thermohaline staircase.

Decades of data collected in the western tropical North Atlantic show that the conditions favorable for the formation of thermohaline staircases are present permanently in this area (Schmitt, 2003). The representative hydrography inferred from HRP dive 125 is shown in Fig. 3. The water column is composed of Subtropical Underwater, a high salinity water mass that overlies Antarctic Intermediate Water, characterized by a salinity minimum. Together, these bodies present a decreasing profile of salinity and temperature with depth, necessary for salt-finger staircase development. Taken within the C-SALT site, seismic Line D2 crosses an area with strong staircases during the spring of 1985, and lies at the border between strong and weak staircases in the Fall of 1985 (Fig. 1). The existence of a thermohaline staircase is thus quite likely in this region. Thermohaline staircases have been observed many times in the area east of the Caribbean Sea since the early days of continuous electronic profiling, including salinity-temperature-depth profiles from 1967 (Mazeika, 1974).

Because turbulent mixing may disrupt the regular structure of thermohaline staircases, they are most apparent where interactions from internal waves, rough topography, boundary forcing and other processes affecting flow stability do not significantly affect their characteristic step-like signature. The staircase imaged in the seismic line extends about 22 km eastward from its position in Fig. 2 at about 190 km to about 212 km, in the depth range of 550-700 meters. However, reflective horizons become less regular and have lower amplitudes westward of about 200 km with the deepest high-gradient layer disappearing altogether in places.

The strength of the vertical salinity gradient, S_z, relative to the temperature gradient, T_z, can be expressed in terms of the density ratio, $R_\rho = \alpha T_z/\beta S_z$, where α and β are the thermal expansion and haline contraction coefficients. We calculate R_ρ from 0.5-m resolution CTD profiles after estimating the gradients as the slope of linear fits to temperature and salinity against depth in 30 m moving segments. Double diffusion due to salt-fingering is strong for density ratios between 1 and 2 and increases as R_ρ approaches unity (Schmitt, 1981). Strong staircases with well-defined layers and interfaces are found where the density ratio is less than 1.7, and the finestructure becomes irregular for R_ρ near 2. Profiles of temperature and R_ρ are shown in Fig. 4 for the HRP dives. Density ratios are low, approaching unity, for short segments of the profiles, most continuously in dive 123, where relatively well-defined steps are observed. The temperature profiles also show intrusions susceptible to diffusive-layering convection. For T and S increasing downward strongest diffusive layering is expected for $1 < 1/R_\rho < 3$ (marked green in Fig. 4b). Although the density ratio favors staircase development for all profiles, strong velocity (Fig. 5) and shear (Fig. 4b) disrupt the vertical structure. The weak velocity and shear recorded in dive 123 allows for the presence of a staircase where $R_\rho < 1.5$. Detailed profiles of temperature and salinity, sound speed and R_ρ inferred from this dive are shown in Fig. 6, in the depth range between 400 and 650 m. Observed temperature and salinity finestructure indicates three well-defined high-gradient steps separating four layers at depths between 520 and 630 m (Fig. 6). Layer thickness increases with depth from about 16 to 35 m. Changes in density are small (not shown) because salinity and temperature largely compensate for each other, but abrupt variations in sound speed are large and occur over depth scales similar to those recorded in the temperature finestructure.

3.2 Reflection coefficients

How does the reflectivity change through a thermohaline staircase? Although the HRP dive 123 shows a staircase, it is somewhat irregular and weak. We therefore use profiles from a C-SALT tow-yo survey to exemplify the reflectivity signature in a staircase (Schmitt et al., 1987). Repeat temperature profiles reveal the staircase where $R_\rho \sim 1.6$, between 300 and 600 m with 5- to 30-m-thick mixed layers separated by 1- to 10-m-thick high-gradient interfaces (Fig 7a). The reflection coefficient profiles calculated here, using the CTD profiles from C-SALT, show large spikes corresponding to sharp changes in sound speed from layers in the step-like structure (Fig. 7b). We next calculate the reflection coefficients from the seismic Line D2, along a 4-km section centered at the structure resembling a staircase (inset in Fig. 1). In the section of the seismic survey centered on the staircase, reflection coefficients show high values with respect to background noise that are laterally coherent throughout the profile (Fig. 8). Absolute values calculated from the seismic data are slightly larger than those from the C-SALT CTD, which may be attributed to errors from noisy data and constructive interference of neighboring high amplitude wavelets. We conclude, however, the reflectivity pattern inferred from the seismic data set is consistent with that expected from a staircase and is indicative of the strength of temperature and salinity contrasts between mixed layers.

3.3 Synthetic analysis

We can estimate the seismic reflection signature expected from the HRP dive 123 staircase by conducting synthetic seismic modeling (Sect. 2.3). Synthetic seismic traces created from density and sound speed profile from dive 123 (Fig. 9) show several hyperbolic reflections corresponding to vertical contrasts in sound speed. Shortly after a high-amplitude linear direct arrival, reflections become visible at a depth of about 200 m. Staircase reflections are the first strong packet of reflections to arrive after the direct arrival between 500 and 640 m, which match the depths with high gradients in the sound velocity profile. The unique step-like banded appearance is seen in both the synthetic and the seismic data (compare insets in Figs. 2 and 9). Reflections with high amplitudes relative to their surroundings are laterally coherent, continuous and closely spaced, and resemble the observed staircase structure in Line D2, which lies ~ 110 km to the west of the station location (Fig. 1). Because the synthetic seismic transect shows all the layers at the correct depths, we conclude that the seismic reflection method is capable of imaging the variations in finestructure that characterize a thermohaline staircase.

3.4 Longevity

Though strong staircases in the area have been observed since the advent of continuously profiling instruments in the late 1960's, the staircases are constantly advected and modified by eddies and internal waves. The longevity of the individual layers has yet to be constrained. Schmitt et al. (1987)

observed in their moored time series that four strong layers retained their identity for the entire eight months between the two C-SALT surveys. This suggests a minimum lifetime of approximately eight months. Several threads of evidence presented here strongly suggest that the feature observed toward the eastern end of seismic Line D2 is a thermohaline staircase. The CTD profile from HRP dive 125 deployed in 2001, co-located with Line D2, intersects the approximate location of the staircase imaged in 1998, but does not contain profiles with the characteristic step-like finestructure. Thus, the staircase had a lifetime of less than 3 years at this particular site. However, since this location is at the boundary of the strong staircase region identified during C-SALT (Schmitt et al., 1987), it seems most likely that the steps have simply retreated from this spot due to the varying ocean currents. It is believed that a staircase can always be found in the thermocline east of the Caribbean, since the strong vertical salinity gradients are maintained by the advection of both the salinity maximum water and salinity minimum water into the region by the general circulation.

3.5 Weak turbulence

Thermohaline staircases are characterized by very low levels of viscous dissipation rate of turbulent kinetic energy (ϵ). During the C-SALT experiment, dissipation rate measured by microstructure measurements, averaged across the entire staircase, was close to the noise level of the measurements, or about $\sim 10^{-10}\,\mathrm{W\,kg^{-1}}$ (Gregg and Sanford, 1987). Although ϵ in a staircase is very low, for the C-SALT staircase, it was found to be eight times larger than predicted for ϵ due only to the presence of internal waves (Gregg, 1989). This is likely caused by additional dissipation associated with the buoyancy flux produced by salt fingers in the interfaces. The dissipation rate from internal waves can be inferred by the finescale parameterization that employs 10-m shear measurements (Gregg, 1989)

$$\epsilon_{\mathrm{IW}} = 7\times 10^{-10} \left\langle \frac{N^2}{N_0^2} \right\rangle \left\langle \frac{S_{10}^4}{S_{\mathrm{GM}}^4} \right\rangle \tag{1}$$

Here S_{GM} and S_{10} are the Garrett-Munk (GM, Garrett and Munk, 1972) and observed, respectively, shear including all vertical wavelengths greater than 10 m, $N_0 = 5.2\times 10^{-3}\,\mathrm{s^{-1}}$ is the reference buoyancy frequency, N is the measured buoyancy frequency, and $\langle . \rangle$ indicates an average over space and time.

We apply Eq. 1 to the HRP finescale velocity profiles in and outside of the staircase to show that internal-wave induced ϵ_{IW} is anomalously low. We then compare ϵ_{IW} to the observed dissipation rate, ϵ_{obs}, measured by the microstructure sensors on HRP to show that $\epsilon_{\mathrm{obs}} > \epsilon_{\mathrm{IW}}$ in the staircase, consistent with Gregg and Sanford (1987). Finally, from an independent method, using spectral analysis of seismic data, we show that spectral signature of reflectors in the staircase is consistent with low ϵ_{IW}.

Profiles of ϵ_{obs} and ϵ_{IW} for HRP dives 123, 126 and 127 are contrasted in Fig. 10. Dive 123 is in the thermohaline staircase whereas the other two dives are outside, with dive 127 located closer to the shelf break. In calculating $\epsilon_{\rm IW}$, we follow Gregg (1989) and obtain finescale shear components from linear fits over 10 m to the raw data and multiply by 2.11 to account for the attenuation of the first-difference filter. We average the 0.5-m vertical resolution observed dissipation rates to 10 m, to be consistent with $\epsilon_{\rm IW}$. Outside the staircase, at dive 127, the dissipation rate is significantly more energetic, possibly explaining the absence of the staircase despite the low density ratio. At the depth range corresponding to the staircase, $\epsilon_{\rm IW}$ at dive 123 is suppressed by two orders of magnitude. Observed dissipation does not show this feature, likely owing to enhanced turbulence as a result of salt fingering. It should also be noted that assumptions in the finescale parameterization and data processing of microstructure data are questionable in conditions favoring double diffusion. The agreement between the observed and predicted dissipation rate for dive 127 is remarkable. Averaged between 400–700 m depth for dive 127, $\epsilon_{\rm IW} = 5.5 \times 10^{-9}$ W kg^{-1}, identical to $\epsilon_{\rm obs} = 6.3 \times 10^{-9}$ W kg^{-1} within the measurement uncertainties. Dissipation rates are less at the location of dive 126 further east with $\epsilon_{\rm obs} = 6 \times 10^{-10}$ W kg^{-1}, in good agreement with $\epsilon_{\rm IW} = 9 \times 10^{-10}$ W kg^{-1}. For dive 123, $\epsilon_{\rm obs} = 2.9 \times 10^{-10}$ W kg^{-1}, comparable to that in the C-SALT staircase (Gregg and Sanford, 1987).

The $\epsilon_{\rm IW}$ profile of dive 123 also shows that the internal wave field is significantly less energetic than the GM field. When averaged in the depth range of well-defined steps, $\left\langle \frac{S_{10}^4}{S_{\rm GM}^4} \right\rangle$ is about 0.8. This is in agreement with Gregg (1989) who found $\left\langle \frac{S_{10}^4}{S_{\rm GM}^4} \right\rangle$ of about 0.6 for the C-SALT staircase. Resulting dissipation rates are very low accordingly. Consistent with our measurements and C-SALT results, we infer a low internal wave signature in the seismic transect in the vicinity of the staircase.

Spectral analysis of reflections from the western part of the line, between 50-150 km is shown in Fig. 11. Following Holbrook and Fer (2005), we compare ensemble-averaged horizontal wavenumber spectra of reflection displacement to the Garrett-Munk tow spectrum (GM75, Garrett and Munk, 1975), as described in Katz and Briscoe (1979). Here, however, we present the slope spectra as described in Sect. 2.4. The GM75 spectrum is scaled by the survey mean $N = 1.9$ ($\pm$ 0.28) cph between 400–1000 m depth, the typical range of the selected reflections. In total 476 and 477 segments of 1600 m length were picked in the open ocean along Line D2, between 60–100 km and 110–150 km, respectively. The average spectrum from each set of ensembles, representative of the open ocean agree with the GM75 level within 95% confidence between 2×10^{-3} and 7×10^{-3} cpm (500 - 125 m wavelengths). At lower wavenumbers the GM75 curve whitens whereas the observed spectra show a slope comparable to the $k_x^{-0.5}$ slope of the high-wavenumber portion of the GM75 spectrum. Average slope from the open ocean samples between 500 - 125 m wavelengths is -0.6 $\pm$ 0.1. This is consistent with Klymak and Moum (2007) who suggested that $k_x^{-0.5}$ is a good model for the internal-wave subrange at low horizontal wavenumbers. The relatively elevated spectral level at 1 km wavelength can be attributed to the Aves Ridge and variable local bathymetry.

Within the thermohaline staircase, 75 segments of 1600 m length are available for spectral analysis. The ensemble-averaged spectrum in the thermohaline staircase, however, contains lower variance, significant at 95% confidence, relative to the samples from the open ocean. The slope at wavenumbers less than 5×10^{-3} cpm is -0.7 $\pm$ 0.2, slightly steeper than the open ocean spectra. In general, energy in the staircase does not compare well with and is significantly less energetic than the GM75 tow spectrum at wavelengths less than 1 km. The spectral level at scales larger than 1 km suggest a background internal wave activity that might lead to weak turbulent fluxes; however, the existence of the regular structure in the staircase shows that double-diffusive fluxes must dominate.

Klymak and Moum (2007) show that the turbulence subrange of isopycnal slope spectra extends to surprisingly large horizontal wavelengths (> 100 m) and can be distinguished with a $k_x^{1/3}$ slope. In our data set, the slope spectra from the reflections are contaminated by noise at high wavenumbers, dominated by the peak at 50 m wavelength due to shot spacing. Following the kink at 7×10^{-3} cpm the open ocean spectra show a $k_x^{1.5}$ slope until 50 m wavelength as a result of noise, and cannot be interpreted in terms of turbulence subrange. Purposefully designed seismic reflection profiling sampling can be used to infer dissipation rates in the ocean, however, this is beyond the scope of our paper.

4 Conclusions

Our study indicates that the seismic reflection method is able to image the step-like structure of a thermohaline staircase. We present a seismic line from the Lesser Antilles which contains closely spaced reflections, horizontally coherent over 4 km, appearing clearly as high-amplitude interfaces separated by increasing distance with depth, from 19 to 25 m. The general area of the western tropical North Atlantic has been known to harbor staircases for at least the last 40 years. Synthetic modeling using the density and sound speed structure from a CTD containing the step-like structure of a thermohaline staircase indicates that the seismic reflection method is able to image it correctly and serves as a validation for our observations. Reflections from the synthetic staircase are closely spaced with amplitudes comparable to those that arrive at the same times in the seismic data. A comparison of reflection coefficients from a strong thermohaline staircase sampled during the C-SALT experiment with those calculated from the seismic data indicate that they have similar spacing and magnitudes, i.e., the seismic line imaged a strong staircase.

Spectral analysis of reflections indicates that the inferred internal wave level in the vicinity of the staircase is anomalously low, relative to adjacent measurements. A finescale parameterization applied to independent measurements of velocity profiles in and outside of the staircase confirm the weak internal wave field and very low internal wave induced dissipation within the staircase. Microstructure measurements show that the observed dissipation rates in the staircase are one order of magnitude less than those outside the staircase. Whether weak internal waves allow the formation of the staircase, or the double-diffusive convection of the staircase suppresses the internal waves via the mechanism of Ruddick (1985), is not known at this time.

A CTD profile taken in 2001 in the location of the staircase imaged in 1998 indicate that the layers are not permanent and have a lifetime of less than three years in this immediate area. Evidence gathered from a combination of seismic observations, modeling, finescale hydrography and currents, and microstructure measurements support the notion that legacy seismic data can be used to map thermohaline staircases. With sufficiently tuned modern data, layer thickness and temperature jumps across interfaces can be inferred from the impedance contrasts and allow for diffusive flux estimates from widely-used parameterizations. Such structural and physical observations can then be compared for a greater understanding of finestructure and mixing processes in the global ocean.

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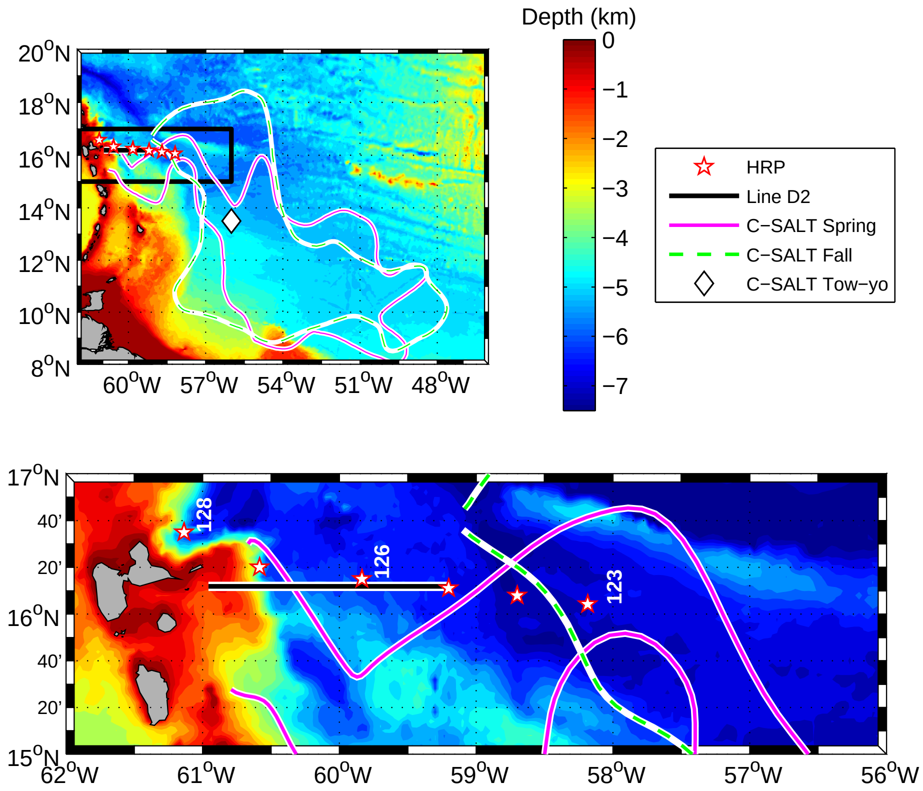

Fig. 1. Bathymetric map of the study area near the Lesser Antilles in the Caribbean Sea. Lower panel is a blow-up of the study region marked by the rectangle in the upper panel. Line D2 (black) is the transect of the 1998 seismic reflection survey. The stations where the high-resolution profiler (HRP) was deployed in 2001 are marked by red stars (dives 123 to 128). Dive 123 (easternmost) is used in the synthetic modeling (Sect. 2.3). Dive 125, at the eastern end of Line D2, is used to constrain the longevity of the layers. The spatial extent of strong staircases identified during the 1985 C-SALT experiment is shown for the spring (magenta) and fall (dashed green) surveys together with the C-SALT tow-yo location (diamond) (Schmitt et al., 1987).

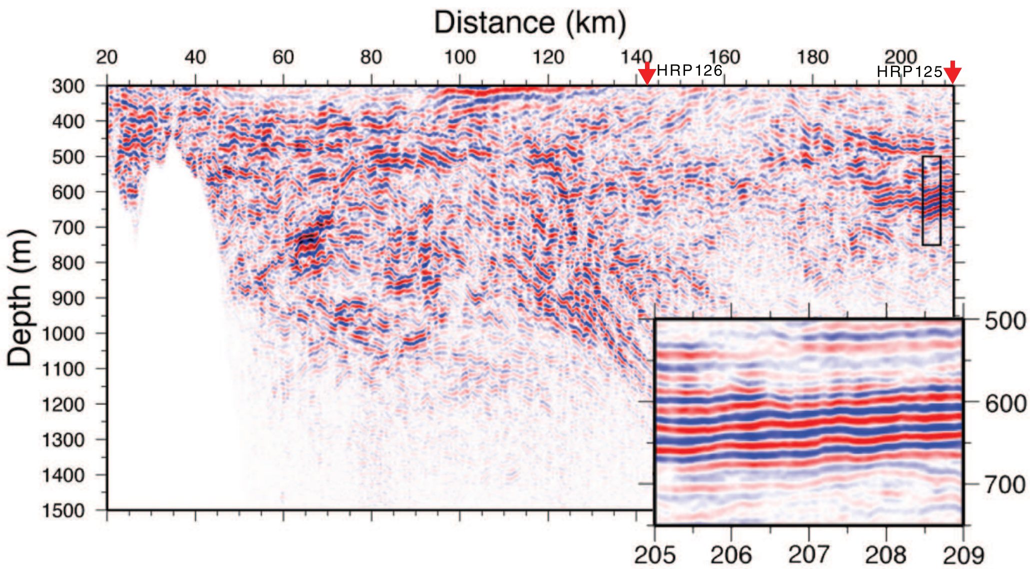

Fig. 2. Vertically exaggerated seismic image of Line D2, collected from west to east across the Caribbean Sea with the shelf of Guadeloupe on the left (masked white). The thermohaline staircase is the high amplitude reflective package (inset) visible from about 190–212 km at depths between 550 and 700 m. These regular, uniformly spaced, banded layers are unique to this part of the section. Relative positions of the HRP dives 125 and 126, collected 3 years after the seismic survey, and approximately 5.8 and 1.6 km north of the seismic line respectively, are marked on top.

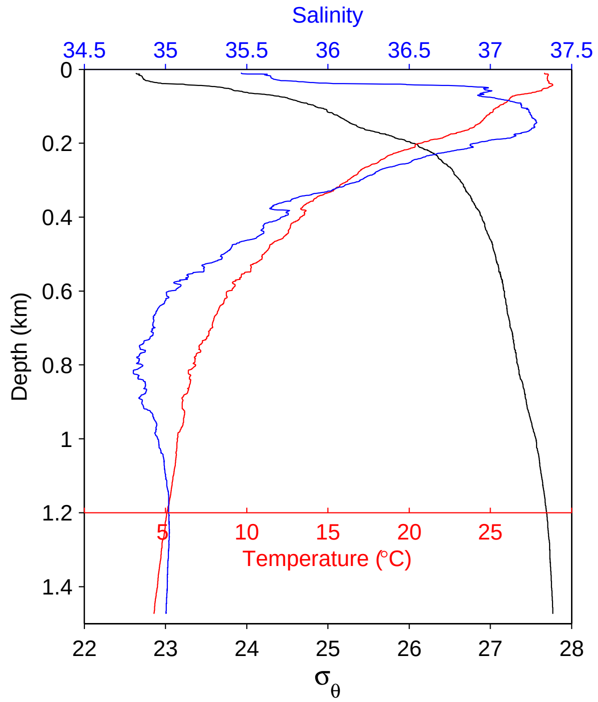

Fig. 3. Temperature (red), salinity (blue) and potential density anomaly (σ_θ, referenced to zero pressure, black) measured by HRP dive 125 near the eastern end of the seismic profile (Fig. 1). Water masses characteristic of this region are the Caribbean Surface Water with a salinity less than 35.5 at depths less than 50 m, Subtropical Underwater at depths 50–200 m and a salinity maximum exceeding 37, and Antarctic Intermediate Water at depths 600–1000 m and a salinity minimum of around 34.7.

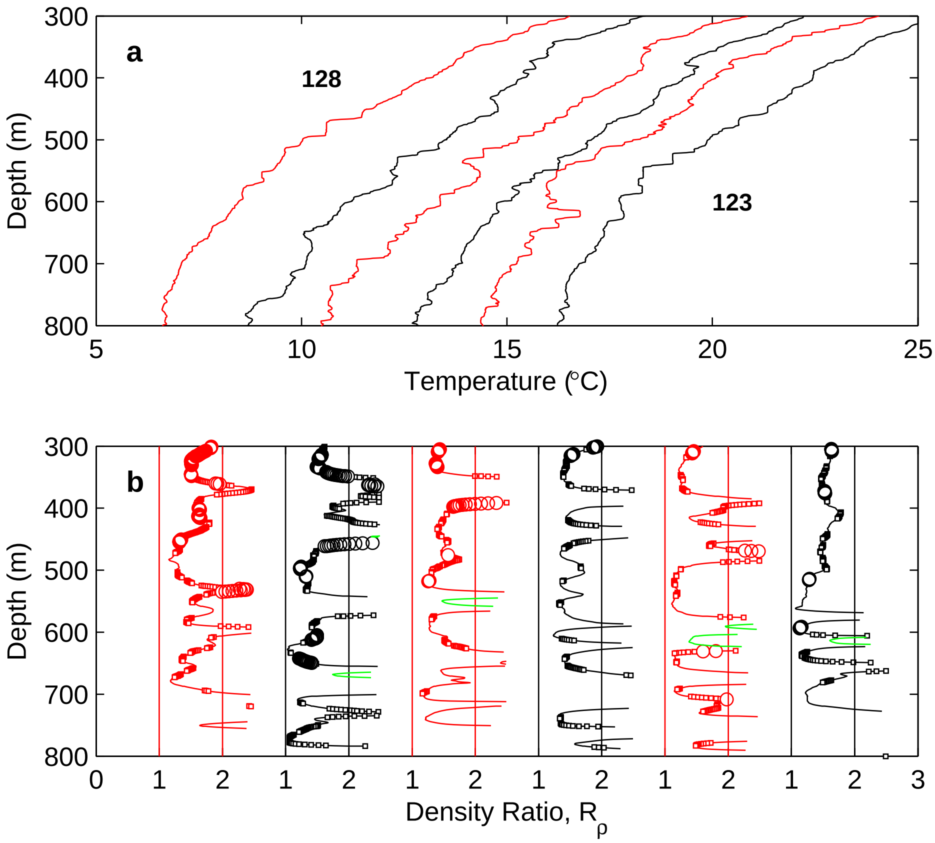

Fig. 4. Profiles of a) temperature and b) density ratio, R_ρ inferred from the HRP dives deployed in 2001. Dive 123 indicates data upon a synthetic seismic study was based. The temperature scale is correct for the leftmost CTD. Each subsequent profile is offset by 2 °C, shown in alternating red and black color. Density ratio profiles are offset and colored accordingly with $R_\rho = 1$ and 2 indicated by vertical lines. $R_\rho > 2.5$ are masked for clarity. The portions favoring diffusive-layer convection $0 < R_\rho < 1$ are highlighted using $1/R_\rho$ (green, shown in the range $1 < 1/R_\rho < 2.5$). The size of the circles are scaled according to the magnitude of 10-m shear ($< 1 \times 10^{-3}$ s^{-1}, no marker; $(1-3) \times 10^{-3}$ s^{-1}; $(3-6) \times 10^{-3}$ s^{-1}; and $> 6 \times 10^{-3}$ s^{-1}, large marker)

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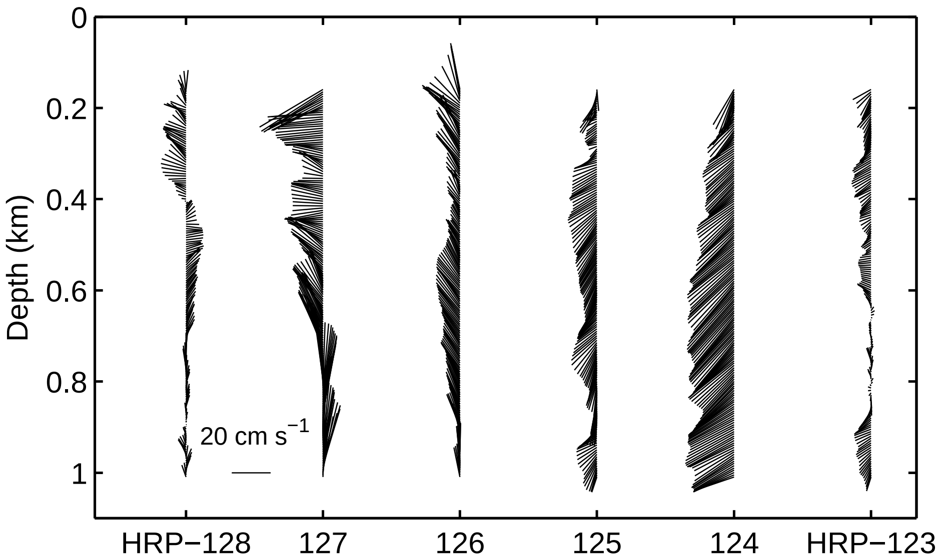

Fig. 5. Profiles of horizontal velocity for HRP dives 123 to 128 shown between 160–1010 m. Velocity vectors from 15-m smoothed profiles are shown at every 5 m (i.e., every 10th data point of 0.5 m vertically sampled profiles).

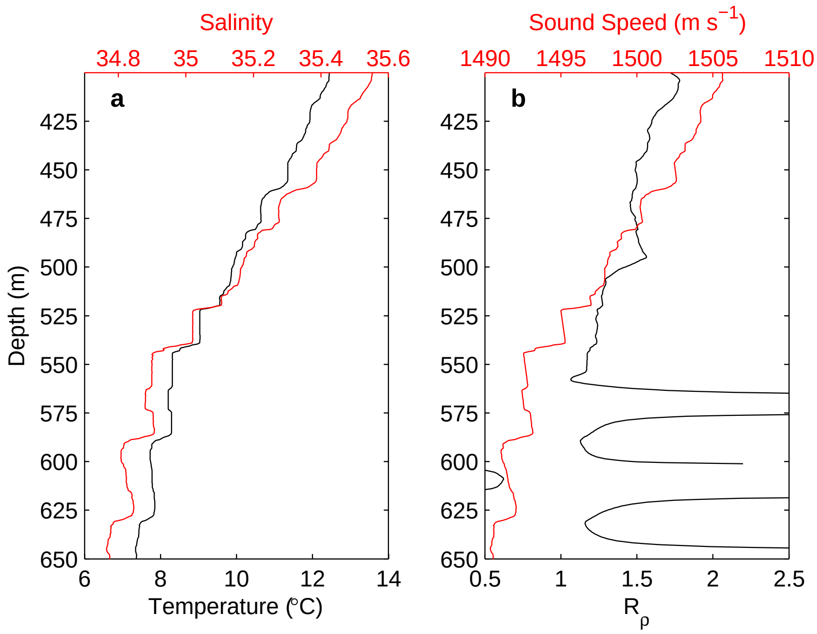

Fig. 6. Profiles of a) temperature and salinity and b) density ratio, R_ρ and sound speed in the staircase (HRP dive 123). Sound speed and in-situ density profiles from this dive are used for the synthetic analysis.

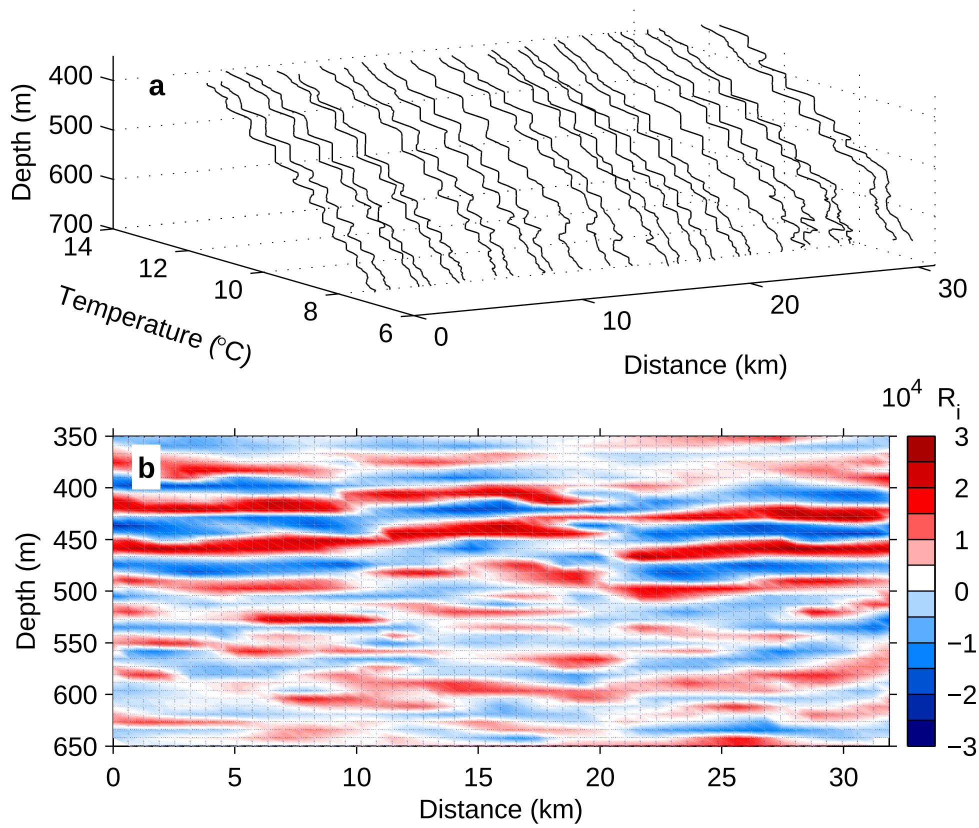

Fig. 7. a) Three-dimensional view of CTD tow-yo temperature profiles collected during C-SALT at a strong, well-defined thermohaline staircase (Schmitt et al., 1987). Distance is inferred from the cumulative great-circle distance between the position at the start of each subsequent cast. b) Reflection coefficients calculated from the C-SALT CTD tow-yo shown in a). Peaks in reflection coefficient correspond to sharp changes in sound speed.

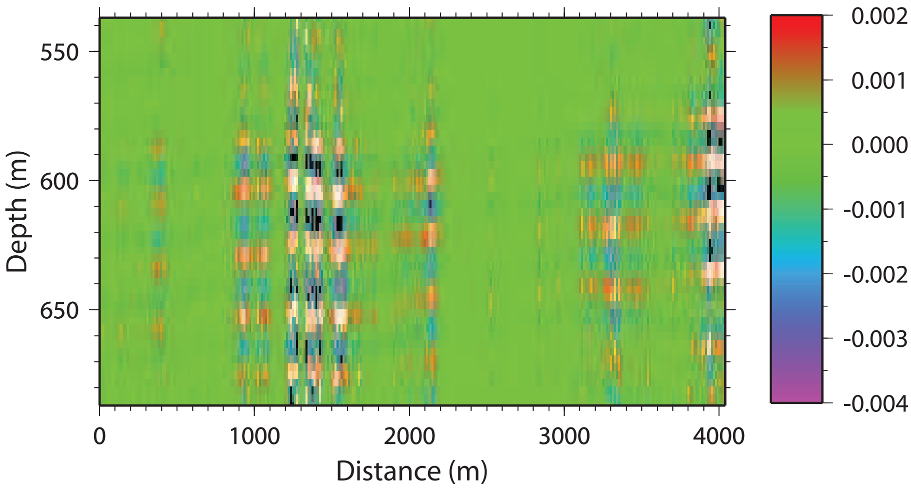

Fig. 8. Reflection coefficients calculated from a section of a 1 km near-offset time-migrated seismic stack, centered on the thermohaline staircase. Values at the high-gradient layers are larger than background noise and show a regular, lateral coherence throughout the profile. High values at 1400 and 4000 m (masked white) correspond to errors caused by a diffraction in the sea floor, only partially corrected by the migration, and extremely low sea floor and multiple amplitudes respectively.

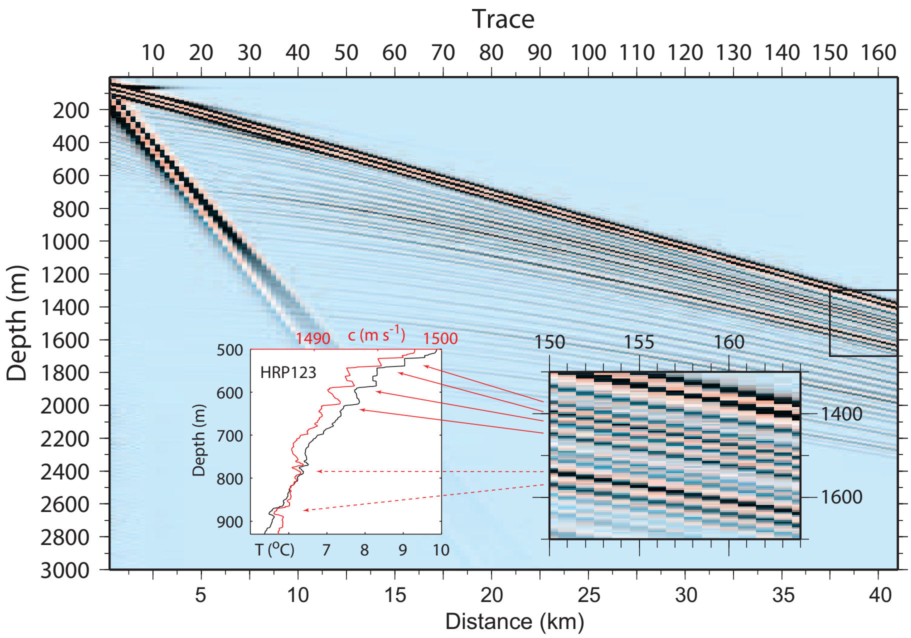

Fig. 9. Unstacked synthetic seismic shot gather using the CTD profile from HRP dive 123 east of Line D2 (Fig. 1). The direct arrival appears as large amplitude linear reflections starting at the sea surface. The airwave appears as the large linear event traveling at low velocity. Reflections from synthetic sound velocity and density structure calculated from the CTD are seen as hyperbolic horizons starting at about 200 m at trace 1, at zero offset, which occurs directly below the source. Reflections from further offsets follow a hyperbolic moveout with respect to the zero offset trace, and are corrected to zero offset before stacking, using the appropriate sound speed to convert from time to depth. Note that only depths at zero offset correspond to depths on a stacked section. The synthetic staircase is imaged as the next strongest coherent packet of four reflections with the same moveout, visible at higher offsets. The insets show (left) a portion of the sound speed and temperature profiles from HRP dive 123 and (right) a blow-up of the synthetic seismic shot gather marked by the rectangle. Red arrows associate the staircase reflections with the measured staircase. Also shown are relatively strong deep reflections associated with the two intrusive features (dashed arrows).

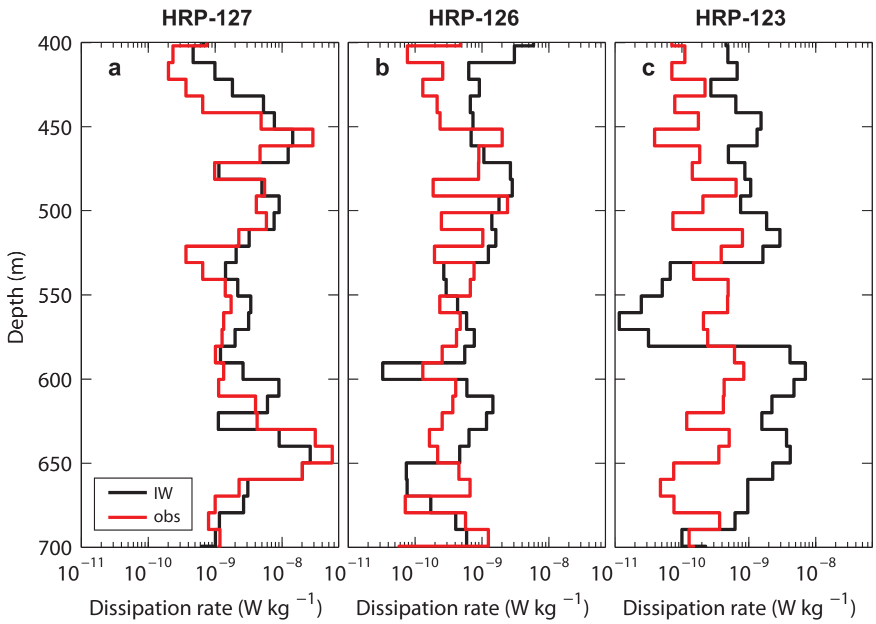

Fig. 10. Profiles of dissipation rate of turbulent kinetic energy (black) inferred using finescale internal-wave parameterization using Eq. 1 (Gregg, 1989), and (red) measured by the microstructure shear-probes for HRP dives a) 127 b) 126 and c) 123.

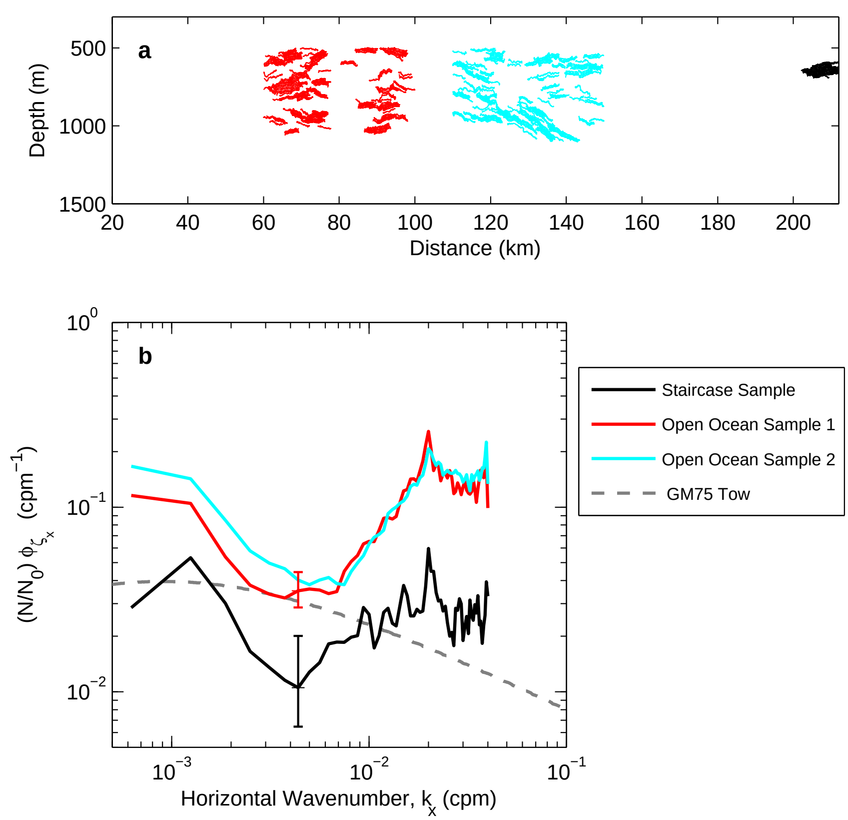

Fig. 11. a) Reflections digitized for spectral analysis for ensembles in the staircase (black), and open ocean samples 1 (red) and 2 (cyan). b) Ensemble-averaged slope spectra of selected horizons in the vicinity of the thermohaline staircase (black) and in the open ocean (red and cyan). All spectra are scaled by the average buoyancy frequency within the depth span of the horizons. Dashed line shows the slope spectrum inferred from GM75 tow spectrum (Katz and Briscoe, 1979) representing the average background internal wave energy for the average buoyancy frequency ($N = 1.9$ cph). The 95% confidence intervals (CI) are indicated for 160 and 25 degrees of freedom, respectively, for the open ocean and staircase spectra, assuming that every 6th reflector is de-correlated vertically (Krahmann et al., 2008). The energy level in the staircase is anomalously low whereas those derived from other horizons scale to a level above the GM75 spectrum.