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Report on hydrographic measurements made at two sites; MAR and DISCOL area

Deliverable 2.6

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¹ NIOZ Royal Netherlands Institute for Sea Research
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26 February 2016
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1. Introduction

A key input expected from WP2 consists of assessing some guidelines for oceanographic monitoring before, during and after mining operations. Collecting in situ data during these three phases of production is essential. First, knowing the background conditions of the surroundings of a mining site is of paramount importance in order to understand and predict (via modelling) the response of a site to human intervention (see also Rabitti & Maas, 2015a). A model-only approach is not feasible at the moment, especially where complex topography and small-scale dynamics dominate, such as is the case for hydrothermal vent fields on the Mid Atlantic Ridge (MAR). Small-scale phenomena are in fact still badly reproduced at such locations, as well as the intertwining of large ocean flows and fronts (at scales of hundreds of metres to kilometres) with smaller scale features, down to the turbulent processes and viscous scales (centimetres and below). However, these interactions are exactly the key to understand the fate of natural or artificial plumes in the deep ocean, plumes as the ones that will be produced during mining operations. According to the data collected and the predictions, a specific site might be considered suitable, or not, for safe and environmentally feasible mining.

Collection of data during the operations is also useful to confirm previous predictions, and monitor the production phase. In case of unexpected outcomes, it would be then possible to stop or modify the activities, in order to prevent major damage or mitigate the response of the environment. After the mining phase, data collection will be useful in order to follow the recovery of the area.

In Rabitti & Maas (2015b), an example of collection and analysis of hydrodynamic data has been given for three case study sites: two hydrothermal vent fields on the MAR and for some locations in the Clarion-Clipperton Zone (CCZ). This report focuses instead on the in situ collection, and analysis of variance and persistence of hydrographic conditions at two case study sites (see Figure 1), chosen worldwide among the potential mining sites of major interest.

![Figure 1: The two case study sites considered: the Rainbow hydrothermal vent field on the Mid Atlantic Ridge, and the DISCOL area in the South Pacific.](image)
As in Rabitti & Maas (2015b), the case studies considered belong to two diverse types of deep sea environment:

1. The Mid Atlantic Ridge (MAR), characterised by high topographic complexity, often with an axial canyon at their spreading centre and transverse canyons on their flanks. In the MAR, we have considered the Rainbow hydrothermal vent field (see Section 2).
2. The DISCOL area (standing for DISturbance - deCOLonization experiment; Foell et al., 1990), a long-term, large-scale disturbance decolonisation experiment in the abyssal eastern tropical South Pacific Ocean (see Section 3).

When considering potential deep-sea mining sites and impact, hydrothermal vent field areas in all oceans are of particular interest for two main reasons. First, these are the places where mineral-rich (copper, manganese, rare earth minerals, etc.) deposits might be found, and thus most likely among the first targets for mining activities. Second, they are natural laboratories for the study of plume dispersion in the deep sea in very complex topographic settings. In fact, high-temperature (of the order of 300°C) vent fields give rise to particle-rich plumes (Figure 2a in Rabitti & Maas, 2015b) rising hundreds of metres above the seafloor, where they spread laterally into the surrounding water column. Understanding the behaviour of natural plumes can help in understanding the future behaviour of artificial plumes produced by mining activities. In fact, at the moment, we do know that the first kind of plume, the natural one, supports unique and fascinating ecosystems, and plays a key role in the dispersal of larvae and chemicals, while we are very uncertain about the potential consequences of the artificial plumes that will be produced in the same environment.

Abyssal plains rich in manganese nodules such as the DISCOL area are also of interest as target mining sites (Figure 2b in Rabitti & Maas, 2015b). Regarding artificial plume behaviour in abyssal plain settings, we can hypothesize that modelling would be simplified because of the flat topography. However, local hydrodynamic and hydrographic conditions and their temporal and spatial variability are also of great importance when predicting the vertical and lateral spreading of the tailings.

For the site on the MAR (Section 2) we will present new in situ, hydrographic data, acquired within the MIDAS project during two oceanographic campaigns in May 2014 (cruise 64PE388, RV Pelagia) and April 2015 (cruise 64PE398, RV Pelagia). Moreover, during the 2014 campaign, three deep-sea, long-term oceanographic moorings were deployed and recovered the subsequent year. Two of them were equipped with hydrographic sensors for temperature and salinity measurements. This allows us to present in this report time series of hydrographic measurements between May 2014 and April 2015 at two locations around the vent field.

For the DISCOL area (Section 3) we describe observations made during two GEOMAR-led cruises during 2015, from 28 July to 25 August and 28 August to 1 October (RV Sonne cruises SO242-1 and SO242-2). These multidisciplinary cruises formed part of the JPI-OCEANS project, revisiting the site where the original DISCOL disturbance experiments were carried out in 1989. Hydrographic observations during SO242-1 and SO242-2 were from lander platforms, from a stand-alone thermistor mooring and from vessel-based CTD profiling.

Focus is here given on the site-specific conditions bearing implications and possibly interactions with mining activities. For details on deep ocean processes of relevance, see Dale & Inall (2015) and Rabitti & Maas (2015a). From an observational point of view, this means that data of relevance come from the vicinity \((O(10)\) m - \(O(10)\) km) of the possible source, and mainly from the lower part of the water column, since the near-bottom environment is obviously of particular interest in this context.
2. Rainbow hydrothermal vent field (MAR)

Within the MIDAS project, the Rainbow hydrothermal vent field on the MAR has been the target of two oceanographic campaigns in May 2014 (cruise 64PE388, RV Pelagia) and April 2015 (cruise 64PE398, RV Pelagia). An analysis on the persistence and variability of the hydrodynamic conditions observed in the area has been reported in Rabitti and Maas (2015b). In this report, instead, the focus is on the hydrographic part of the measurements collected during the same two campaigns. It follows that the site introduction, the description of the data collection and the data set for the two reports largely overlap. The relation between hydrodynamics and hydrography of the site is also discussed.

The Rainbow hydrothermal plume was discovered during a geophysical survey along 200 km of the MAR in 1996 (German et al., 1996), and it is the strongest - in terms of plume spatial spreading - of the several new sites of hydrothermal activity located during that survey. The Rainbow hydrothermal vent field is located at 33º 54.12' W, 36º 13.78'N, SW of the Azores Triple Junction, approximately 20 nautical miles outside the Portuguese Exclusive Economic Zone (EEZ). The field is at an average depth of 2300 m and comprises about ten high-temperature (365º C) vents (Dymant et al., 2009; German et al., 2010).

The main literature references for this site are Aleynik & Lukashin (2005), Cave et al. (2002), Dymant et al. (2009), German et al. (1996, 1998, 2010), Thurnherr (2006), Thurnherr and Richards (2001), and Thurnherr et al. (2002).

2.1 Data, instruments and methods

The data set presented in this report has been collected during two multi-disciplinary cruises (64PE388 in May 2014 and 64PE398 in April 2015) with RV Pelagia in the Rainbow field area, combining the scientific goals of the Treasure (Dutch) and MIDAS (European) projects. The Treasure
team focused on geological and biological aspects of the area, while the MIDAS team on its hydrographic and hydrodynamic characterisation. The MIDAS goals have been achieved using a variety of instruments. During the 2014 cruise, an intense hydrographic and hydrodynamic survey was performed consisting of 41 stations, arranged in a telescopic set of circles, centred around the Rainbow field (see Figure 2a). Radial distance from the vent area of each circle of stations is: 0.5 km, 1.3 km (not visible because superposed in Figure 2a), 3.5 km, 9.4 km and 25 km. At each station, a Sea Bird 911-plus CTD profile has been acquired, measuring the classical Conductivity-Temperature-Depth, but also turbidity (Wet Labs, ECO-NTU sensor), fluorescence and oxygen content. After post-processing, all profiles have a vertical resolution of 1 m, with a range between about 5 m below the surface to 20 m above the bottom, a conservative choice due to the bottom roughness of the sampled area. In 2014, the CTD Rosette was also equipped with an LADCP (Lowered Acoustic Doppler Current Profiler). Results from these velocity measurements have been presented in Rabitti & Maas (2015b).

Besides the single CTD/LADCP stations, in 2014 a 13-h station was also performed (white square in Figure 2b), NE of the Rainbow field, to assess the hydrographic and hydrodynamic variability of the area on a tidal time scale. The whole water column has been sampled in the 10 acquired profiles. Moreover, three tow-yo stations have been performed sailing west to east across the western flank of the Rainbow hill between 1700 m depth and the bottom (black thick line in Figure 2a), west to east on the eastern flank of the Rainbow hill between 1700 m depth and the bottom (blue thick line in Figure 2a), and southwest to northeast into the canyon north of the Rainbow hill between 1700 m depth and the bottom or 2300 m (green thick line in Figure 2a). These measurements have been acquired yoyo-ing with the CTD while sailing at 0.5 knot, allowing for a detailed characterisation of the three transects.

In 2014, three oceanographic moorings have been deployed in the vicinity of the Rainbow vent field, in order to monitor the current velocity field and hydrographic properties in the bottom part of the water column at three different locations: in the near field, downstream and upstream of the plume injection, and in the far field, downstream of the field (see Figure 2b). All three long-term moorings have been successfully recovered during the 2015 cruise, with no loss of instrumentation. Unfortunately, we did experience some instrument failure. The design of the three moorings is sketched in Figure 3, depicting only well-functioning instrumentation. Details on positioning are given in Table 1.

In tables 2, 3 and 4, a summary of the data obtained from each mooring is presented, with details on instrument depths and record lengths. In short, all three moorings consisted in a bottom, upward looking ADCP (Acoustic Doppler Current Profiler), with an ensemble averaging period of 1200 s (20 min). Above the ADCP, the moorings were equipped with Nortek AquaDopp or Aanderaa RCM-11 current meters for hydrodynamic measurements, and with SBE 37-SM microcats for hydrographic time series, according to Figure 3. Sampling rate for current meters and microcats has been 600 s (10 min). Again, results from velocity measurements have been presented in Rabitti & Maas (2015b), while here we will focus on the hydrographic part of the data set.
In this work, spectra of time series are obtained using the multitaper method, with three discrete prolate spheroidal sequences as data tapers for the multitaper estimation (Percival, 1993; Thomson, 1982).

Table 1: Mooring locations, see Figure 2b.

<table>
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<th>Latitude (dec deg)</th>
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<tr>
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<tr>
<td>M3</td>
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Table 2: Details for M1, near-field, north-east of plume source; see Figure 3, left panel.

<table>
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### Table 3: Details for M2, far-field, north-east of plume source; see Figure 3, central panel.

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### Table 4: Details for M3, near-field, south of plume source; see Figure 3, right panel.

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<td>23-Mar-2015 05:58:03</td>
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<tr>
<td>Aanderaa</td>
<td>1283</td>
<td>24-May-2014 15:47:00</td>
<td>10-Apr-2015 14:49:00</td>
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**Figure 4**

a) Mean flow around the Rainbow Ridge from mooring measurements. Brown, orange and yellow colours represent ADCP measurements: brown for the near-bottom currents, orange for measurements at about 2100 m, yellow for measurements at about 1900 m. Blue colours represent current meter measurements: dark blue for measurements below 1000 m, light blue for measurements above 1000 m.

b) Sketch of the mean flow regime from Thurnherr and Richards (2001). Thick black arrows represent the hydraulically controlled flow below 2000 m; dashed line indicates the region where enhanced mixing is expected; white arrows represent the flow above 2000 m.

### 2.2 Results and discussion

**Regional circulation settings:** Time averaged values and directions are presented in Figure 4a. Brown colours represent ADCP measurements: dark brown for the near-bottom currents, orange for measurements at about 2100 m, yellow for measurements at about 1900 m. Note that at M3 they all almost superpose, and at M2, the near-bottom current is almost covered by the mid-depth ADCP measurements.
Blue colours represent current meter averaged values and directions: dark blue for measurements below 1000 m, light blue for measurements above 1000 m. For comparison, in Figure 4b, from Thurnherr and Richards (2001), a similar sketch of the mean flow regime is reported, using measurements from a single cruise in 1997. In Figure 4b, solid arrows represent the flow below 2000 m; dashed line indicates the region where enhanced mixing is expected; white arrows represent the flow above 2000 m.

With the new, long time series available (Rabitti and Maas, 2015b), we can confirm that the deep, near-bottom layer, hydraulically and topographically controlled flow is separated from the layer above (above 2000 m, in Thurnherr and Richards (2001)’s definition, above 1900 m in our measurements). Its behaviour seems to be quite robust through time, since the deep flow pattern is quite close to 1997 expectations (Thurnherr and Richards, 2001), including the re-circulation patterns to the north-east of the Rainbow hill. This separation is most likely due to the presence of the Rainbow hill (top is 1950 m deep) and of the canyon flanks (about 1900-2000 m deep), shaping the current field.

However now, thanks to the shallower current meter measurements (around 1000 m), we can also distinguish a shallower layer, that on average is moving westward, in accordance to the general circulation, within a sub-tropic gyre. Moreover, we can also distinguish between measurements above and below 1000 m, which zones seem to be affected by different processes.

2.2.1 Hydrography

It took approximately one week of continuous sampling to complete the whole scheme in Figure 2a. It follows that the different profiles have been acquired at different times, and at different tidal phases. We will see in Section 2.2.3 what changes can be related to tidal variability. For the moment, we will take these hydrographic measurements as a quasi-synoptic overview of the hydrographic properties of the area.

The Rainbow site is located at the Mid Atlantic Ridge. Its hydrography is influenced by several large scale features: the Mediterranean outflow, the Azores Current and front, and the complex ridge topography. The topographic setting is further complicated by the presence of the Rainbow hill, which partially blocks the rift valley below 1950 m and separates the valley in southwest and northeast basins. This topographic complexity is expected to reflect also in the hydrographic properties below 1950 m.

Although practically no difference is visible between the two basins in (Thurnherr & Richards, 2001), this is not the case in our observations for the shallower layers. In Figure 5 the mean water characteristics of the two deep basins southwest (SW) and northeast (NE) of the Rainbow hill are compared to each other as well as to the characteristics of the eastern (E) and western (W) off-ridge, background stations. The depth range considered is 500 - 2700 m. Potential temperature and density contours are referenced to 2000 dbar. The two farthest stations in the SW and NE (see Figure 2a) are here excluded. The two basins present almost indistinguishable water masses in the deeper part of the basins, while differences are present in the shallower regions. In particular, the signature of the Mediterranean water is much stronger in the NE basin than in the SW. The Mediterranean water tongue consists of a layer of approximately constant salinity in the $\theta_2$ range of 8-10°C. The mean salinity maximum observed is 35.6 psu associated to a potential density $\sigma_2 = 36.3 \text{ kg m}^{-3}$. The value of salinity is 0.2 psu higher than the one reported in (Thurnherr and Richards, 2001). We can see how the water masses slowly change through space in Figure 6. A sudden shift is observed only for the most southern station (not included in calculations for Figure 5). Moreover, in Figure 5, no clear difference is observed between the eastern and the western background water, it is thus not immediate to originate the rift valley waters to one of the two sources.
Figure 5: Mean water characteristics of the two deep basins, southwest (SW) and northeast (NE) of the Rainbow hill compared to the characteristics of the eastern (E) and western (W) background, off-ridge stations. Depth range is 500 - 2700 m. Potential temperature and potential density contours are referenced to 2000 dbar.

Figure 6: Same as Figure 5, but here for the ten stations sampled following the track NE to SW in Figure 2a. Blue is the most northern station in the NE quadrant (start), yellow is the most southern station in the SW quadrant.
An overview of the isotherms during the whole cruise is given in Figure 7, where the four reconstructed transects are displayed. In colour, we can appreciate the spreading of the plume in the NE-E direction, while little to no trace of the plume is detected in the SW basin. More on this in Section 2.2.2. The 15°C isotherm (not shown in Figure 7) is detected at around 170 m in the SW basin, and around 210 m in the NE basin, meaning that we sampled the Azores front region for the whole cruise (Thurnherr and Richards, 2001). However, surface salinity values were higher than expected (around 36.40 psu). Criteria to assess if a given station lies north or south of the Azores Front follow those in (Thurnherr and Richards, 2001): - depth of the 15°C isotherm: if < 300 m, and around 100 m, station lies north of the front; - surface salinity: < 6.4 psu, around 36.2 psu, station lies north of the front.

Figure 7: Overview of the four transects, reconstructed from the measurements as displayed in Figure 2a. In the title of each panels, the direction of the track followed by the ship. In colour, turbidity is displayed on an arbitrary scale, yellow colours indicating more particle scattering. In the deep sea (below 1500 m), elevated turbidity values indicate the presence of the Rainbow plume. The Rainbow site is indicated by a red triangle. Superposed are isotherms (black lines, deg C).

Figure 8 shows a comparison of profiles of potential density referenced to 2000 dbar, buoyancy frequency N, and turbidity for four stations, two far from the hydrothermal source, representative of the southwest basin (yellow line) and of the northeast basin (purple line), and two close to the hydrothermal source, upstream (SW, red line) and downstream (NE, blue line). The comparison is made for the same depth range 1700-2700 m. Inspecting single stations (in 8a) instead of average properties (Figure 5), we notice that indeed the deepest waters present different properties in the SW basin and in the NE basin. The densest water is present in the SW basin, as in (Thurnherr and Richards, 2001). However, the separation of the two waters takes place, as expected, around 2000-
2100 m, and it is probably due to the presence of the Rainbow hill. This fits nicely with the separation of different flow directions and regimes, taking place around the same depth, as seen in the previous section and in (Rabitti and Maas, 2015b). In Figure 8a, density steps, as layers of constant density, are evident only in the two profiles close to the source. Spatial scale of the step is 50-100 m. The largest step in the NE, close to the source is around 2100 m and it corresponds to the strongest signature of plume in turbidity (Figure 8c). Several steps are present however also in the SW station close to the source, where no signature of the plume is detected. Step layering of the water column in plumes is very characteristic at all Mid Atlantic Ridge sites. Transparent “windows” were found in the plumes of Snake Pit, Broken Spur and previously in Rainbow (Aleynik and Lukashin, 2005). It is still not clear, however, to what extent these layers relate to the presence of the plume, or to effects of double diffusion in the form of salt fingering, that can form steps with varying lengths in vertical profiles of temperature, salinity and density.

In Figure 8b profiles of the buoyancy frequency N are presented. Enhanced stratification is present in the two stations close to the source at the depth level of the top of Rainbow hill (2000 m), with values of 1 - 1.2 x 10^-3 s^-1. Below 2100 m, values are similar for all stations, around 0.5 x 10^-3 s^-1, similar to the ones observed in (Thurnherr and Richards, 2001).

![Figure 8: Comparison of profiles of (a) potential density referenced to 2000 dbar, (b) buoyancy frequency N, and (c) turbidity for four stations, two far from the hydrothermal source, representative of the southwest basin (yellow) and of the northeast basin (purple), and two close to the hydrothermal source, upstream (SW, red) and downstream (NE, blue). The comparison is made for the same depth range 1700 -2700 m.](image-url)

Differently from (Saunders and Francis, 1985), the stratification of rift valley water appears not to be reduced in comparison to the abyssal waters found on either side of the ridge (background stations, not shown). The idea was that rift walls would block recirculation, resulting in reduced stratification and thus in greater plume rise heights. The reduction in stratification is however not observed in our dataset, where, below 1800 m, rift valley waters and background water show comparable values of N.

Values of vertical diffusivity, estimated using Thorpe scales (Thorpe, 1977) from CTD data, are high (~10^-2 m^2 s^-1) when compared to average deep sea values (~10^-4 to 10^-3 m^2 s^-1, see for example Waterhouse et al., 2014), since they are relative to a very rough portion of the ocean floor (MAR). Within the transect, values of diffusivity are higher ~ 10^-1.5 m^2 s^-1 near the steep topography than farther away, presenting a vertical and horizontal spatial variability on the 50 to 100 m scale (not shown). Evidence of downstream enhanced diffusivity is clear from Figure 8c, where the NE profile, far from the source, is characterised by a general level of turbidity higher than the SW profile. We interpret this as a signature of mixing of the plume with the ambient water. We confirm this finding with the tow-yo transects, see Figures 9, 10 and Figure 12, where the green and blue transects in Figure 2, in the middle and right panels of Figure 12 respectively, present a more diluted and vertically spread plume (400 m against 100 m at the source).
Figure 9: Plume detected by turbidity measurements. (a) Overview of 2014 cruise. Stations where an increased turbidity has been detected between 2000 m and 2200 m are marked in purple. The suggested plume spreading is shaded. Figure from Henko de Stigter, Treasure project. (b) Three-dimensional view of the plume spreading around the Rainbow hill. Composite image obtained using the three tow-yo transects (see thick lines in Figure 2 for tracks), inserted in the bathymetric map. The red triangle represents the vent field location. View is towards north-east. Colour represents an arbitrary scale for turbidity.

Figure 10: Estimation of suspended matter concentration (gram of dry mass per cubic meter) in two combined tow-yo transects (red line in Figure 9a) crossing Rainbow Ridge in West-East direction, approximately 2.2 km north of Rainbow vent field. The conversion from optical backscatter to suspended matter concentration has been performed using filtered water collected in situ. These are preliminary results by Henko de Stigter, Treasure project.
2.2.2 Plume detection using turbidity and CTD profiling

a) Turbidity signature of the plume

Results from the 2014 cruise on the Rainbow plume dispersion in the surrounding area show a plume signature in turbidity in the depth range 2000-2200 m, with a single or double peak around 2100 m (as in Figure 8c), following the 3.9° C isotherm (Figure 12, top panels).

The plume, released by the hydrothermal vents at about 2300 m on the western flank of the Rainbow hill, is observed travelling northward, strictly constrained by the northward-directed mean flow and the bathymetry (Figure 4). When entering in the northern part of the canyon, it deflects eastwards, following the 2100 isobath, where it gets more vertically and horizontally diluted (Figure 10). A plume signature in turbidity has been detectable more then 20 km North-East of the source, while no plume has been observed south or south-west of the source, even at the closest stations (about 500 m from the field centre).

This picture is however not stable in time. In fact, during the 2015 cruise, few CTD profiles have been also acquired with the same instrumentation set. Although the 2015 cruise was performed in April, with only one month difference with the 2014 cruise (May), sea conditions were very different between the two cruises, and, most importantly, a different spatial distribution of the plume, in terms of turbidity signature, emerged. In 2015, in fact we observed a strong signature in turbidity as far south as 4.2 km southwest of the plume source (Figure 11, purple line). Moreover, the plume has also been detected at about 3 km right north of the source (Figure 11, yellow line), showing that the strong topographic control that was keeping the plume close to the northern tip of the Rainbow hill, observed in 2014 is not always present, and that the area affected by the plume might be larger than the one observed in 2014. Most importantly, these observations show that the plume dispersal pattern is highly variable in time, and confirm previous findings on the area. At the Rainbow site, (Aleynik and Lukashin, 2005)
report also an inter-annual variation in plume vertical position in the range of one-to-two hundred meters.

Several mechanisms can contribute to this variability. However tidal, inertial (local inertial frequency is around 20 hours) and other relatively high frequency effects are not likely to be driving this change. Their excursion scales would tend to be smaller (shorter than a kilometre), and thus do not match with the observed, much larger scales of pattern variability (larger than a kilometre). However, large amplitude internal waves (tidally generated) can in principle travel long distances (Zhao et al., 2010). We hypothesise that perhaps here a lower frequency mechanism(s) comes into play. Altimeter data over the cruise periods might possibly link changes in spatial plume spreading to deep penetration of upper-layer, eddy-like features (both surface and meddies). Furthermore, for the Rainbow vent field we can also not exclude a high variability in plume discharge rates and volumes from its multiple sources, as was observed on many MAR sites in the late 1990s and early 2000s. Unfortunately, we are not able to check this latter hypothesis with the available dataset.

Figure 12: Left panels correspond to the black transect in Figure 2, central panel to the green transect, right panels to the blue transect. Upper panels: temperature field superposed on the turbidity measurements for the three tow-yo transects. Lower panels: isopycnic temperature anomalies (green: -0.05°C, blue: -0.015°C, red: +0.015°C) superimposed on the turbidity measurements.

b) Density and temperature signature of the plume

The presence of an enhanced turbidity layer might not be the only signature of the presence of a hydrothermal plume. We also expect a signature in the density and temperature fields. In the lower panels of figure 12 isopycnic temperature anomalies are shown superposed on the turbidity measurements. Green contours correspond to a -0.05°C anomaly, blue contours to a -0.015°C anomaly, red contours to a +0.015°C anomaly. In (Aleynik and Lukashin, 2005) the negative temperature anomaly (~ -0.06°C) related to the plume (due to the entrainment of the near bottom layer with a bit colder waters) was usually located above the layer characterised by enhanced turbidity. This was explained in terms of stratification properties: the relatively strong stratification of the water column in the Atlantic Ocean leads to partial separation of the density plume from the
turbidity plume. However, in the present dataset, a negative anomaly ~ -0.05º C (green contours in lower panels of Figure 12) is observed above the plume, but only in the central and eastern transects. Remarkably, the anomaly is not observed above the plume in the vicinity of the source, where, instead, an isopycnal temperature anomaly of ~ -0.01º C (blue contours in lower left and central panels of Figure 12) is observed within the turbidity plume. This behaviour is similar to the near-source scenario depicted in (Thurnherr & Richards, 2001), where an isopycnal temperature anomaly of ~ -0.019º C/V (turbidity is measured here in Volt) is observed. We speculate that the temperature and turbidity anomalies could be superposed within the plume in the near field, and then get separated while the plume is spreading in the surroundings. Further analysis in this direction will help in assessing the role of the temperature anomaly on top, or within, the plume, perhaps shading some light on unusual, local stratification conditions that may affect vertical mixing of the water and plume particles. Care in fact has to be taken when considering the water layer above the plume, at depth 800 - 1500 m. There, highly saline and warm Mediterranean water can be often found. This 'contamination of plume signal", with its high temperature and salinity variability, can in principle obscure both the hydrological impact of hydrothermal activity on the water characteristics and can also make it more difficult to determine the upper boundary of the density plumes. Because of its deeper location, this mechanism should not affect the Rainbow plume (situated around 2100 m), however has to be taken into account if one is considering shallower locations of the plume source (e.g. the Lucky Strike vent field, not far from Rainbow).

2.2.3 Tidal variability of hydrographic characteristics

One of the many difficulties regarding the interpretation of hydrographic (as well as hydrodynamic) surveys as the one presented here lies in the problem of splitting spatial and temporal scales, especially the tidal time scales. Local tidal variability has been assessed thanks to a 13-hour CTD/LADCP yo-yo station (10 casts in total, figures 13 and 14). The hydrographic and current measurements have been performed at about 1.3 km NE of the Rainbow field, on the western flank of the Rainbow hill, between approximately 5 m from the surface to 20 m above the bottom, at about 2250 m. The observation of the presence or absence of the Rainbow hydrothermal plume detected by optical turbidity measurements (Figure 14), performed at the same time of the velocity measurements (Figure 13), is very informative, as well as puzzling. In fact, although in the near-bottom layer the current direction is not dramatically changing throughout the 13 h, implying the presence of a strong topographically-steered, rectified current, a strong time variability of the presence of the plume is observed (see presence or absence of thin, black arrow within the corresponding colour coded arrow in Figure 13). We exclude, as possible explanation for this plume variability, the changing strength of the current. The plume is detected or not despite the magnitude of the measured velocities being more or less strong. It simply seems that the plume was not there for the first 3 casts of the series, until about midnight, while it was always detected in the subsequent profiles. We cannot exclude, here, a variability of the plume emission itself, but we have no measurements to confirm or reject this hypothesis. Moreover, it was also noted in Thurnherr and Richards (2001) that in the stations closest to the Rainbow vent field, both the horizontal and the vertical variability of the plume (detected via optical turbidity measurements) was the highest, in accordance to what was observed at other hydrothermal sites.
Figure 13: Current speed and direction as measured by the LADCP averaged in three depth layers, according to panel titles. Colour of the arrows represents time, from blue to yellow, see colour scheme in 6. First cast started on the 18th of May 2014, 19:47 UTC, last cast started on the 19th of May 2014, 07:03 UTC. A thin black arrow is superposed on the colour arrow when the plume is detected using turbidity measurements, as displayed in Figure 14. More on tidal variability of currents in Rabitti and Maas (2015b).

Figure 14: The ten turbidity (NTU) profiles during the 13 h, tidal sampling. On the x-axis, time UTC. (a) the whole water column, (b) zoom in the 500 m next to the bottom. Isotherms are superposed in both panels.

Figure 15 Potential temperature - salinity diagrams for the 13 h measurements. (a) for the depth range 0 – 2250 m, (b) for the depth range 1700 - 2250 m (as in Figure 14b). Colour indicates time, from blue to yellow.
Although looking at the whole water column (Figure 14a) the situation seems static for the whole 13h, between 1700 m and bottom (about 2250 m, Figure 14b) isothermal lines exhibit a wave-like structure consistent with the semidiurnal internal tidal wave. The doming of the isotherms (as well as of the isopycnal, given the tight relation between temperature and salinity, see Figure 15) is indicative of the rotating wave regime and the corresponding radiating lee wave (Gill, 1982), as observed previously in Thurnherr and Richards (2001). The phase of the isoline displacement appears to slightly vary with depth, suggesting vertical propagation of the wave. The maximum displacement observed is about 150 m, near the bottom, with an average displacement of about 50 m. Near the bottom the structure is also showing more complexity, with a tight relation with the plume dispersal, embraced by the 3.8 °C and 4 °C isotherms.

Looking at the potential temperature - salinity diagrams for the 13 h measurements (Figure 15), (a) for the depth range 0 - 2250 m, (b) for the depth range 1700 - 2250 m (as in Figure 14b). Colour indicates time, from blue to yellow. Below 2000 m, tidal effects are thus confirmed to be weak compared to hydraulically controlled (Figure 13, right panel), as well in terms of water mass composition (Figure 15).

2.2.4 Long-term variability of hydrographic characteristics

a) Time series

Over the duration of the time series (of nearly one year), temperature and salinity both weakly decrease (figures 16 to 21). Temperature sensors have been calibrated at the deployment and at the recovery, so the decrease of temperature with time is genuine. No correlation with the low-frequency currents was observed though, see figures 18 to 20, and neither do we see a strong impact of storms (except, perhaps, in October, Figure 18). Water composition is extremely stable throughout time, the largest excursions being present in the shallower measurements, Figure 21c. At mooring M1, differently from mooring M2, the decrease in temperature is visible in Figure 21a through time (shift in position between blue dots, early period, and yellow dots, for a later period). However the dots are moving approximately along the isopycnal line of 1036.8 kgm³.

b) Spectral analysis

Spectral analysis of the measurements in Figure 22 gives information on the dominant frequencies for the variability of hydrographic properties. According to our estimates, for buoyancy frequency N = 0.5 x 10⁻³ s⁻¹ at 2300 m (see Section 2.2.1), corresponding to an buoyancy period of about 3.5 hours (1/7 day), the full internal wave window is then covered by the measurements. A spectral drop off is indeed visible near this frequency in the shallowest spectrum, Figure 22c. In panels 22b, d and f, a zoom between 9 to 29 h is displayed. This is done to appreciate the spectral behaviour in this period window, relevant for tidal and inertial (around 20 h) variability.
Figure 16: Raw measurements of (a) temperature, (b) salinity and (c) derived density from the microCAT at M1. Time goes from May 2014 to April 2015. Ticks denote the beginning of the month. Thin light lines show all measurements. Thicker, darker lines correspond to a 25h-moving average of the signals.
Figure 17: Same as Figure 16, but here for the deep (left) and shallow (right) microCAT at M2.

Figure 18 (a) same as Figure 16a, (b) zonal, u, and meridional, v, velocity as measured at the same location and comparable depth by the moored ADCP (for details see (Rabitti and Maas, 2015b)). The signals have been smoothed with a 25h-moving average. Time for the ADCP measurements goes from May 2014 to December 2014.
First, as we expected also from results in (Rabitti and Maas, 2015b), the inertial peak is evident only above 2000 m. Below this depth, little to no signature of near-inertial frequency is found. Near-inertial waves are thus probably triggered at the surface by near-inertial wind stress, and are not able to reach the bottom, whose dynamics appears more tidally dominated. However, spectra of temperature time series (Figure 22) reveal a difference when compared to spectra of velocity time series (Figure 11 in Rabitti and Maas, 2015b). In fact, in the zonal velocity spectrum at mooring M1, we have observed a strong, unexpected near-bottom enhancement of the K1 tidal component that reaches and even exceeds the M2 and S2 tidal components. This was possible since the K1 tidal component is subinertial in this region and thus is prone to trapping by the topography, while super inertial waves (as for example the M2 and S2 tidal components) cannot be trapped. Interestingly, this strong local effect of K1 enhancement in the zonal velocity is not visible in the temperature spectrum, where the sharp K1 peaks have no difference at location of mooring M1 and at location of mooring M2. Bottom enhancement of the semidiurnal, M2 tide, however is clearly visible at site M2, compare Figures 22d and 22f. While this is expected in a stratified sea over sloping terrain (Maas and Zimmerman, 1989), and may be of importance to spreading of plume material, the hydrothermal vent cannot be traced directly in terms of representing anomalous spectral behaviour.

Figure 19 (a) same as Figure 17a, (b) zonal, u, and meridional, v, velocity as measured at the same location and comparable depth by the moored ADCP. The signals have been smoothed with a 25h-moving average. Time for the ADCP measurements goes from May 2014 to March 2015. Although the ADCP at M1 and M2 were approximately at the same depth, note here the different velocity range in comparison with Figure 18b.
This confirms that the near-bottom layer around the Rainbow hydrothermal vent fields is in principle tidally dominated, but not in a trivial way. This is because of the complex local topography, allowing for hot spots and trapping of certain frequencies. These trapping mechanisms in the vicinity of the Rainbow hydrothermal plume source might have in principle big consequences on the spreading pattern of the plume particles. It follows that it has to be taken into account that similar mechanisms could also play a role in the vicinity of a mining site, deviating the plume path, and enhancing, or dumping, its vertical spreading.
Figure 21 Potential temperature - salinity diagrams for the three moorings. (a) mooring M1, 2300 m (b) mooring M2, 2188 m, (c) mooring M2, 1867 m. Colour indicates time, from blue to yellow. Only one measurements every 15 h is represented in the Figure.
Figure 22: Spectral analysis for the temperature signal from M1 (a,b), and M2 (c to f). The left panels show the whole spectrum covered by the measurements (periods go from 256 days to approximately 22 minutes = 1/64 of a day), the right panels show a zoom between 9 to 29 h, relevant for tidal motions. Black vertical lines mark the main tidal components (labelled according to convention), while the dashed vertical line corresponds to the local inertial frequency $f \left( f = 2\Omega \sin \phi \right.$, where $\Omega$ is the Earth rotation rate and $\phi$ the local latitude).
3. DISCOL

The DISCOL Experimental Area (DEA) lies within a manganese nodule field in a region of relatively gentle abyssal topography in the Peru Basin of the eastern tropical Pacific, with a typical bottom depth of around 4150 m (Figure 23). Observations at the time of the original experiment (Klein, 1993) provide a picture of the physical context as one of variable background velocities, which exceed 5 cm/s at times, and a bottom mixed layer of 100-200 m in height. The DEA was the target of two GEOMAR-led cruises during 2015, from 28th July - 25th August and 28th August - 1st October (RV Sonne cruises SO242-1 and SO242-2). These multidisciplinary cruises made a wide range of observations, with hydrographic data (table V) obtained from lander platforms, from a stand-alone thermistor mooring and from vessel-based CTD profiling. New disturbance experiments were also carried out using an epibenthic sled and the plumes generated were monitored.

![Figure 23 Bathymetry of the DISCOL area with the DISCOL Experimental Area (DEA) circled in red. The BoBo lander, DOS lander and thermistor mooring sites are indicated. This figure represents an area in excess of 600 km² with a depth range of around 400 m. Source: SO242-1 cruise report.](image)

3.1 Data, instruments and methods

3.1.1 Bobo lander

The NIOZ BoBo (Bottom Boundary layer) lander is a 4-m high, long-legged tripod lander, left panel of Figure 24, designed to study currents and sediment transport near the seabed (Weering et al., 2000). Current profiles in the 2 m above the seabed were measured with a downward-facing RDI 1200 kHz ADCP in the centre of the lander frame, while an upward-facing RDI 300 kHz ADCP mounted in the top of the frame recorded current profiles up to several tens of metres above the lander. The lander was further instrumented with a Seabird 16plusCT (conductivity and temperature), a WetLabs ECO-FLNTURTD (chlorophyll and turbidity), and a Technicap PPS4/3 sediment trap.
During SO242/1 the BoBo lander was deployed two times for short durations, of 5 and 10 days, first in the undisturbed area three miles south of the DEA, and then in the disturbed area near the centre of the DEA. During both short deployments a resuspension experiment was carried out in which the lander served for recording the sediment plume generated by towing an epibenthic sled within a relatively short distance of the lander. The lander was subsequently deployed for a third time in the undisturbed area to the south of the DEA, and recovered 31 days later during SO242/2.

### 3.1.2 DOS lander

The GEOMAR Deep-Sea Observation System (DOS) lander, right panel of Figure 24, is based on a multipurpose platform (Pfannkuche and Linke, 2003) and was instrumented with an RDI 300kHz upward-looking ADCP, a KUM sediment trap with up to 21 bottles, a Seabird 16plus CTD (conductivity, temperature and depth) with Wetlabs ECO-FLNTURTD (chlorophyll and turbidity), and an Ocean Imaging Systems stereographic camera system. The DOS lander was deployed three times for 4 to 7 days during SO242/1, and for a final 31-day deployment with recovery during SO242/2 (Table 5).

![Figure 24: BoBo (left) and DOS (right) landers. Source: SO242/1 cruise report.](image)

### 3.1.3 Thermistor mooring

The NIOZ thermistor mooring was instrumented with 201 NIOZ-4 thermistors and three AquaDopp acoustic current meters. The NIOZ-4 self-contained temperature sensors sample at 2Hz with precision better than 0.001°C and a low level of noise. Sensors were taped at 2 m vertical intervals to a nylon-coated steel cable, with the lowest sensor 6 m above the bottom and the upper sensor 406 m above the bottom. The sensors were synchronized via induction every 6 hours, leading to a timing mismatch of less than 0.04 s. The Thermistor mooring was deployed during SO242/1 and recovered during SO242/2, yielding a time series of 60 days in length.
Table 5: Summary of hydrographic observations made at the DISCOL site during 2015.

<table>
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<tr>
<th>Instrumentation</th>
<th>Latitude (d:mm.mmm)</th>
<th>Longitude (d:mm.mmm)</th>
<th>Date of deployment</th>
<th>Date of recovery</th>
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<td>-7:07.408</td>
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<td>28/9/15</td>
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<td>30/7/15</td>
<td>05/08/15</td>
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<tr>
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<td>-88:28.497</td>
<td>06/08/15</td>
<td>16/08/15</td>
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<td>-7:07.422</td>
<td>-88:25.538</td>
<td>16/08/15</td>
<td>16/09/15</td>
</tr>
<tr>
<td>Seabird 16plusCT</td>
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<td>-88:26.086</td>
<td>06/08/15</td>
<td>16/08/15</td>
</tr>
<tr>
<td>Wetlabs ECO-FLNTURTD</td>
<td>-7:07.422</td>
<td>-88:25.538</td>
<td>16/08/15</td>
<td>16/09/15</td>
</tr>
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<td>SBES3plus temperature</td>
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<td>Digiquartz 410K pressure</td>
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<tr>
<td>Wetlabs FLNTU fluorescence</td>
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<tr>
<td>QCP2300-HP PAR SBE43</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>dissolved oxygen</td>
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</tr>
</tbody>
</table>

3.2 Results and discussion

These are relatively new data sets, so analysis is ongoing and is not described in detail here. Velocity time series from the landers show peak current speeds of around 6.5 cm/s, with a significant semi-diurnal tidal component (Figure 25). This picture is consistent with prior observations. These time series are being used to predict advection of the plumes generated by the epibenthic sled in order to interpret the plume signals detected at lander locations figures 26 and 27. The addition of the thermistor mooring data will provide understanding of hydrodynamic processes in the bottom boundary layer, a key determinant of plume evolution.
Figure 25: Current speed (mm/s) and direction (degrees from north) at approximately 15 m above the bottom, recorded during successive BoBo (pink) and DOS (blue) lander deployments. These time series span all deployments during SO242/1, and locations may differ between deployments.

Figure 26: Lander-based observations of turbidity and ADCP backscatter during artificial disturbance experiments, showing periods of elevated values resulting from the passage of plumes.
Figure 27: The position of epibenthic sled disturbance tracks (lines) and the first BoBo lander deployment (circle) (in UTM coordinate). Curves show predicted advection tracks for the generated sediment plume based on the downward-looking lander ADCP.
4. Conclusions and implications for deep-sea mining activities

As mentioned in (Rabitti and Maas, 2015b), the goal of hydrodynamic (as well as hydrographic) characterisation of a site in the context of deep-sea mining is the understanding and, possibly, the prediction of the final spatial distribution of the mining plume. This knowledge is crucial in order to foresee the physical, biological and ecological consequences of mining activities, and thus enabling the interested parties in planning operations that will be environmentally feasible and safe. However, going from observations to predictions, given also the use of dedicated numerical models (see for example Aleynik et al., 2015), is not an easy task. The horizontal and vertical spreading of a natural and/or artificial (mining) plume is determined by processes involving a wide range of different temporal and spatial scales, from minutes to seasons, from centimetres to kilometres. For this reason, a complete and detailed characterisation of three sites, accounting for all relevant phenomena, is at least unrealistic, given the project time and resource constraints, and falls far beyond the scope of this report.

Here we have limited ourselves to the description of the hydrographic data sets collected within the MIDAS project on two sites: the Rainbow hydrothermal vent field, on the Mid Atlantic Ridge (II) and DISCOL, in the South Pacific (Section 3). In particular, we have been interested in the characterization of the sites, their spatial and temporal scales of variability, and their stratification and vertical mixing properties.

In fact, an understanding of the local hydrography and flow regime is of paramount importance in interpreting physical plume observations, such as those in Section 2.2.2. Without detailed knowledge of the background hydrography it is not possible to determine the role of present temperature and density anomalies.

For the Rainbow site, we have been also able to trace and study the plume spreading around the source. This dataset, together with the hydrodynamic information from (Rabitti and Maas, 2015b), help us identifying processes that could potentially lead to increased vertical mixing or current speeds, with consequent enhanced horizontal spreading of the mine tailings material or injections of material into the upper parts of the water column.

In this report, we have only used in situ observations. We remark that observations have to be carried out in the near field of the sites, as well as in the far field, to be able to interpret changes in the region of interest against those occurring on the larger, basin-scale. Satellite data can also be used in combination with in situ observations, to study the influence of surface or intermediate forcings on near bottom dynamics. Moreover, time series of current measurements, possibly at least one year long, are also very important to assess both the local current field amplitude values and directions, as well as its spectral content, and its seasonal modulation.

A combination of hydrodynamic and hydrographic data is essential in order to characterise the site and assess its status before, during and after mining operations, a task that could be requested from interested industries in a not so far future.
5. **Acknowledgments**

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6. **References**


