MIDAS

MANAGING IMPACTS OF DEEP SEA RESOURCE EXPLOITATION

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MANAGING IMPACTS OF DEEP SEA RESOURCE EXPLOITATION

A metric-based decision tree to enable operators to draw conclusions from the probable fate of discharged contaminants from deep-sea mining activities

Deliverable 2.7

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Contents

1. Introduction

Plumes are transported by currents and mixed or stirred by diffusive processes. The flow environment of the deep sea was described in MIDAS Deliverable 2.1. While the deep sea can be typified as a low-energy environment with relatively weak flows, it is also frequently complex and turbulent. Understanding of the nature of this environment across the wide range of temporal and spatial scales which have a bearing on mining plumes is only partial, limited by the observational difficulties of the deep sea and the computational cost of making sufficiently highly-resolved model simulations. The challenge, therefore, in a mining context, is to distil what is known or inferred about the deep sea flow environment into a form that is useful for decision making purposes.

Despite the uncertainties and knowledge gaps, it is possible, to some extent, to categorise deep-sea environments using a set of metrics – bottom slope, level of eddy kinetic energy, etc. – and this is the approach taken here. This report aims to provide a decision-making framework for predicting some generalities concerning the likely behaviour and fate of mining plumes based on such metrics. The focus is on potential mining sites, specifically considering two types of site (Fig. 1): abyssal sites of the sort that provide opportunities for nodule harvesting (e.g. in the Clarion-Clipperton Zone), and topographically complex sites (e.g on mid-ocean ridges), which provide opportunities for mining polymetallic crusts or Seafloor Massive Sulphides (SMS). It should be emphasised that the ocean is a diverse place, and its complexity cannot be perfectly distilled into a set of metrics, so metric-based methods must always be backed up by 'sanity checks' and consideration of all other available information for a given site.

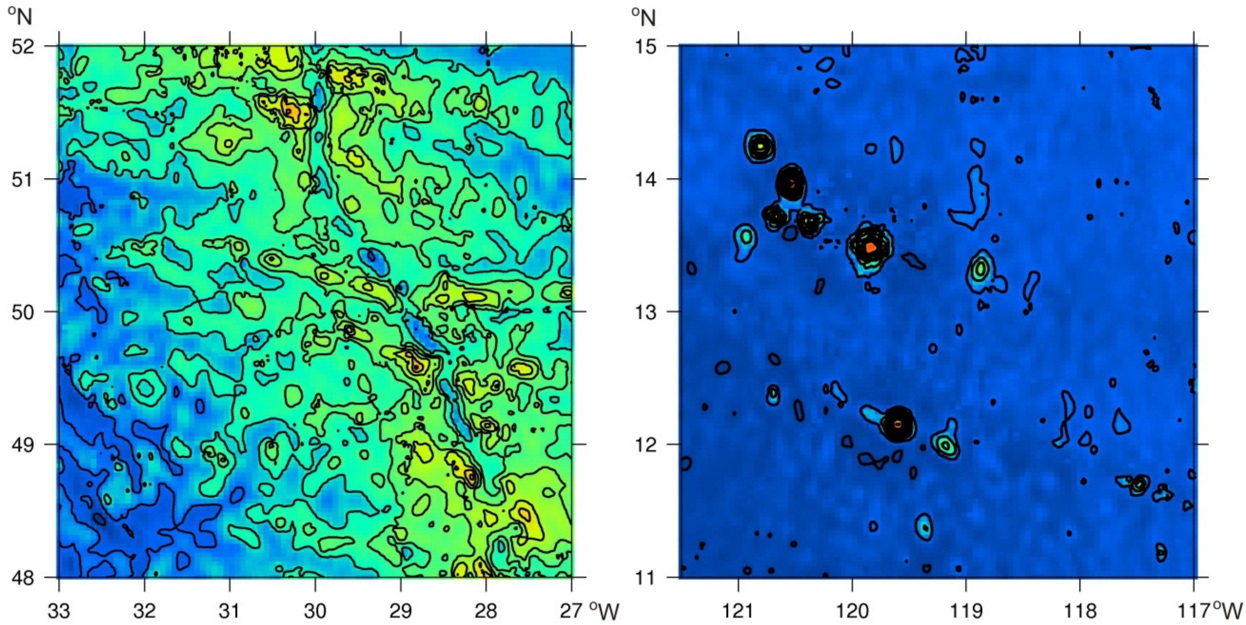

Figure 1. *Two contrasting deep sea topographies from (a) the Mid-Atlantic Ridge and (b) the Clarion-Clipperton Zone of the Pacific, based on satellite derived data (Smith and Sandwell, 1997). The contour interval is 500 m.*

2. The link between current speed, mixing intensity and plume impacts

In considering the nature of plumes and their impacts on differing sites, it is first necessary to clarify which aspects of the flow environment influence the behaviour of a plume, and how they influence it. Clearly the first order influences on plume dynamics are the strength and variability of the current at the plume site, as well as the level of mixing and horizontal stirring. These processes transport the plume away from its source and mix it with surrounding waters. As a plume spreads from its source, the spatial structure of the flow environment becomes important. Its shape may become more complex as it is entrained into eddies, fronts, overturns, gravity currents, etc. The scale of flow structures that need to be considered is limited by the distances over which significant plume impact occurs, so it is important to understand the thresholds of impact in order to focus attention on the scale of physical processes that are most important. Clearly flow structures in the immediate surroundings (e.g. within kilometres) of a mining operation will always be important, but structure on the mesoscale to ocean basin scale are only important if components of the plume have significant toxicity or other impact at very low concentrations.

If a mining operation is generating a plume at a fixed site in a steady background current then the link between the current speed and the concentration and spread of the plume can be expressed in relatively simple terms. Firstly, in a faster current, a greater quantity of water passes the mining operation in a given time. When plume material is being discharge or suspended at a known rate, therefore, the initial dilution is greater. Once plume material is in suspension, its residence time within the water column depends on its behaviour in the vertical dimension – its settling velocity and any vertical movement due to mixing – and this vertical behaviour is not *directly* modified by the current speed. So, if the time that material spends in the water column is comparable at different current speeds, plume material will tend to travel further when currents are faster. This means that far-field impacts will be enhanced, for which there must be a balancing decrease in near-field impacts, because material is more effectively removed from the near-field by the stronger current (Fig 2). This displacement of impact from near- to far-field is expected across a range of impact metrics: plume concentrations within the water column, settling rates on the seabed, or accumulated settlement depth on the seabed.

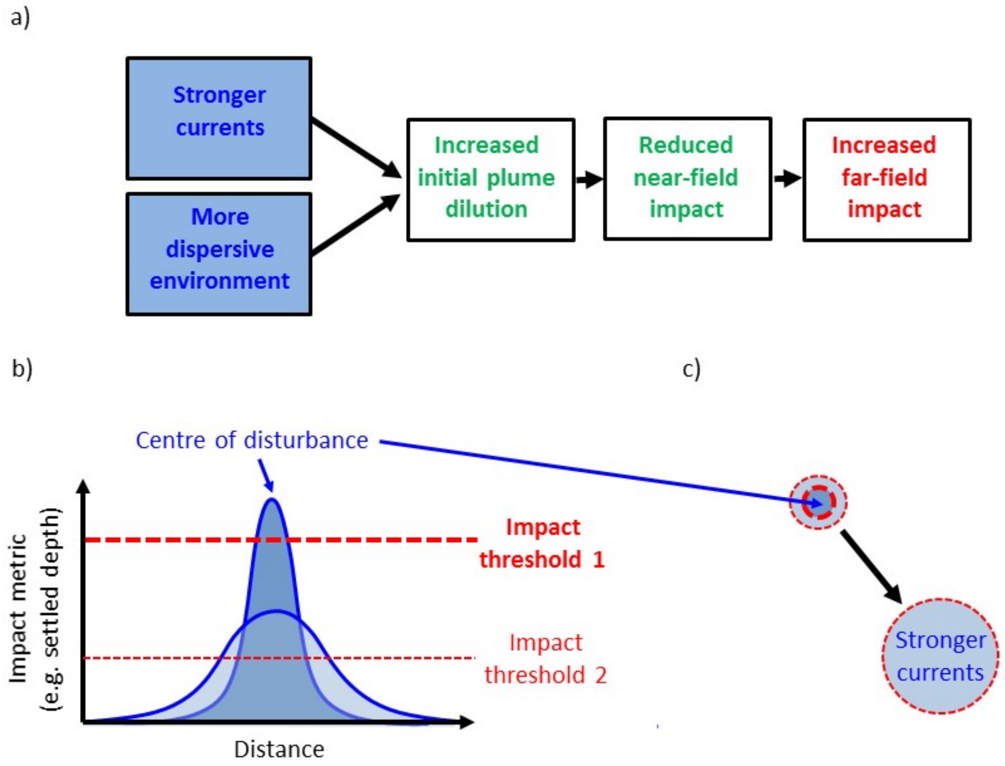

Figure 2. *Summary of the impact of increased current speed or dispersion on the spatial distribution of plume impact relative to two threshold levels. a) Schematic; b) Transect; c) Plan view. Currents and dispersion are assumed to be without directional bias. Stronger currents or greater dispersion lead to a wider impact that does not exceed a high threshold 1, but the area that exceeds a lower threshold 2 is increased. The total quantity of plume material suspended or discharged is constant.*

Stronger mixing/diffusion (vertical or horizontal) acts in a similar way to a stronger mean flow, in that it will either directly stir plume material away from the impacted area or will mix material higher in the water column with the result that it takes longer to settle and therefore is transported further before it reaches the bed.

Whether this displacement of impact from near-field to far-field represents an increase or decrease in the overall impact of the operation depends on how impact is defined. For instance, defining the overall impact in four differing ways (and see Fig. 2):

1) Impact metric: Total quantity of plume material suspended by the mining operation.
   Change in impact when current speed increases: ***No change in impact***.

2) Impact metric: Total quantity of plume material transported outside the mined area.
   Change in impact when current speed increases: ***Impact increases***.

3) Impact metric: Area exceeding a low threshold of concentration or settlement.
   Change in impact when current speed increases: ***Impact increases***.

4) Impact metric: Area exceeding a high threshold of concentration or settlement.
   Change in impact when current speed increases: ***Impact decreases***.

When changes in the near-field impact are balanced by opposite changes in the far-field impact, there will be points in the 'mid-field' where there is little or no change in impact. To illustrate this aspect, a series of simulations have been carried out of the plume impact resulting from a year of nodule collection in the CCZ. One nodule harvesting machine is assumed to cover a 12 km x 12 km box via a 'lawn mower' pattern of collection (a scenario that is detailed in Appendix A), suspending a defined quantity of the ambient sediment. The background flow in these simulations was derived from a near-bed current meter and the sediment particle size range from analysis at a CCZ site. The simulations used observed current speeds, which were assumed to be spatially uniform, and reasonable values for mixing and stirring represented by vertical and horizontal diffusion coefficients. The resulting impact is presented as a total accumulated depth of settled sediment after the year of operation (Fig. 3). Settled depth decreases rapidly from around 10 cm within the mined area to less than 1 cm beyond a range of a few kilometres, to less than 1 mm beyond around 10 kilometres. The pattern of settlement shows distinct 'rays' corresponding to favoured directions of flow.

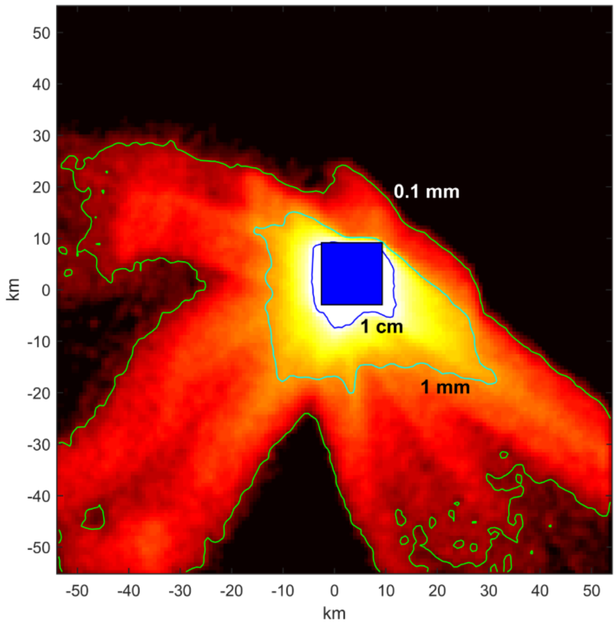

Figure 3. *Illustrative map of settled sediment depth in a realistic scenario in which plumes of ambient sediment are suspended by nodule harvesting within a 12 km square region (blue box) during the course of a year. Shading represents the settled depth of sediment and contours of sediment depth are shown with order of magnitude intervals. Full details of this scenario are given in Appendix A.*

Starting with the base case of Fig. 3, the current speed was varied by multiplying the observed velocities by factors of 2 and 4 (Fig. 4). The pattern of settlement clearly differs in these cases. The ray-like pattern of deposition evolves, and there is an appreciable expansion of the area exceeding 1 mm or 0.1 mm of settlement. There must also be a compensating decrease in settlement in the near-field. These changes, however, are perhaps more subtle than would be expected. Similarly, varying the diffusion coefficients used over several orders of magnitude (Fig. 5; essentially covering the extremes that might be encountered in the real-world environment) does lead to slightly differing patterns of settlement, but the changes are again relatively subtle, and the range over which settlement levels exceed, say, 1 cm or 1 mm do not drastically change.

The perhaps surprising lack of sensitivity displayed in Figs. 4 and 5 results from the fact that the total quantity of plume material entering the water column is constant and the metric of impact was the settled sediment depth. If, for instance, the maximum water column concentration was used then this would show great sensitivity to the vertical diffusion coefficient because the vertical extent of the plume would increase. As a rule of thumb, increasing the vertical diffusion coefficient by two orders of magnitude increases the vertical extent of the plume by one order of magnitude and decreases concentrations accordingly by one order of magnitude.

In summary, these simple sensitivity studies clarify some aspects of the influence of current speed and levels of mixing on the behaviour of plumes, and the following sections provide an aid to diagnosing these factors for a given site. It is, however, very important to be clear what the metrics of impact are.

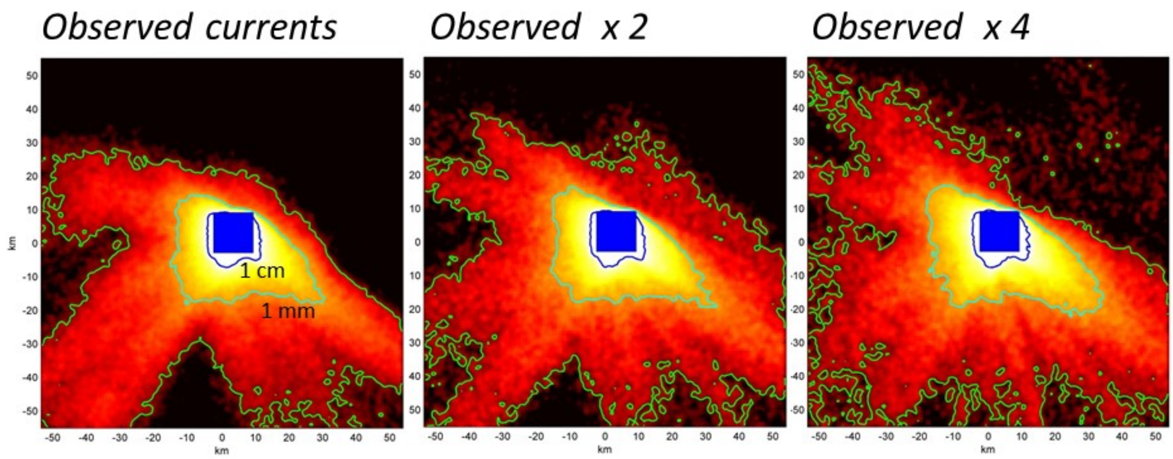

Figure 4. *The effect of increased current speeds on settled sediment depth. The left hand panel shows the base case (as Fig. 3). The other two panels show the effect of increasing currents speeds by factors of 2 and 4.*

3. Metrics to describe the hydrodynamic environment

The nature and variability of the deep-sea flow environment was described in MIDAS Deliverable 2.1. Some aspects of this environment can be distilled into simple metrics or binary distinctions (e.g. between complex topography and non-complex topography). There is a risk of over-complicating this process, however. As an illustration, the interaction between currents and isolated topographic features has been a topic of extensive research which has revealed a complex set of flow phenomena which do, in principal, reflect a set of flow parameters (Baines, 1995; Chapman and Haidvogel, 1992; Turnewitsch et al., 2013). The complexity of the potential flow states and the broad set of relevant parameters (dimensions of the feature, background flow speed, level of stratification, contribution of tides, latitude, etc.), however, would not yield a useful decision making tool, and such a tool would be restricted to idealised features. So, the approach here is one of simplicity with the intent being to identify broad classes of site in terms of their hydrodynamic nature.

3.1 Direct drivers of plume behaviour

As described in the previous section, the direct drivers of plume behaviour are the currents that transport material, and the diffusive processes that mix them or stir them vertically or horizontally. Strictly speaking the distinction between currents and diffusive processes is artificial, as 'diffusion' is achieved by small scale stirring by currents, but the distinction does translate readily to models in which small-scale flow structures are represented by diffusive processes since they are not directly resolved. There follows a short overview of typical current speeds and diffusivities in the deep sea for comparison with potential mining sites (again, these were discussed in more detail in MIDAS Deliverable 2.1).

Current speed: In very broad terms, currents are stronger in the upper water column than the lower water column, and stratification (the vertical gradient of density) also decreases with increasing depth. Significant flows do exist at depth, however, with a global average of near-bottom current speed (in depths over 1500 m) being 8-9 cm s^{-1} (Scott et al., 2010), although this figure may be biased towards areas close to significant boundary currents so is likely higher than would be typical of the abyssal Pacific or mid-ocean ridge sites where near-bed currents may be considerably weaker, except at rare sites where large scale circulation is constrained.

Vertical diffusivity: The level of mixing is most usefully described by a vertical diffusion coefficient, here denoted k_z. While the nature of turbulence is that it is patchily distributed in time and space, and diffusion coefficients vary over several orders of magnitude, patterns do emerge in the global distribution of k_z. An excellent summary, based on an extensive dataset, is described by (Kunze et al., 2006), with higher values toward the seabed and over areas of topographic complexity. As a rule of thumb, $k_z = 10^{-4} m^2 s^{-1}$ would be a relatively large diffusivity for a deep sea environment, with greater levels found in mixing hotspots resulting from flow-topography interaction.

3.2 Diagnostic metrics

The decision tree described in the next section uses simple metrics and yes/no decisions to very broadly characterise deep sea environments:

Topographic complexity (yes or no): The level of vertical mixing in the deep sea shows a clear relation to the complexity of topography (Polzin et al., 1997), with mixing being greater in topographically complex regions. While a metric describing the level of topographic complexity could be defined, the simple approach here is to use a binary distinction between 'complex' sites (e.g. mid-ocean ridge) and 'non-complex' site (e.g. abyssal sites, including those with scattered abrupt topographic features, which are considered below).

Proximity of topographic features (yes or no): In otherwise relatively flat abyssal regions, isolated abrupt topographic features are frequently present. These features may have downstream effects on currents and mixing, including lee waves, hydraulic flows/jumps or other wake phenomena (e.g. a vortex street of eddies) (See MIDAS deliverable 2.1).

Bottom slope: Currents encountering slopes are displaced vertically, generating internal waves and tides. Internal waves may break when they encounter a slope. A range of boundary phenomena are also possible against steep slopes, including turbidity currents, bores, slope currents, etc. As a result, conditions close to steep slopes are likely to be more complex and turbulent than elsewhere. Bottom slope should be estimated wherever possible using high-resolution multi-beam bathymetry or the proportion of steep slopes will be significantly underestimated (Becker and Sandwell, 2008). Since tidal interaction with slopes is the major source of turbulence, the most useful metric of bottom slope is the ratio between the bottom slope itself and the slope of internal tidal rays,

$$\alpha = \sqrt{\frac{\sigma^2 - f^2}{N^2 - \sigma^2}},$$

where σ is the tidal frequency, N is the buoyancy frequency, and f is the Coriolis parameter. When $\frac{h_x}{\alpha} = 1$ the slope termed critical. Critical slopes or steeper (supercritical) slopes are associated with significantly greater vertical mixing.

Surface eddy kinetic energy (EKE) from satellite altimetry: Eddy kinetic energy is the kinetic energy of the varying component of a velocity time series (i.e. the energy of the anomaly from the mean). Surface eddies may penetrate to the sea floor at abyssal depths, especially in areas of relatively flat bathymetry. High eddy kinetic energy at the surface therefore suggests high eddy kinetic energy throughout the water column, and provides a convenient measure since satellite altimetry is globally available. As a rule of thumb, low EKE < 200 cm^2s^{-2} and high EKE > 200 cm^2s^{-2}. Note that deep EKE values from direct current measurements are substantially lower in view of the weaker flows at depth.

4. Decision trees describing the fate of mining-related sediment plumes and discharges

Decision trees for simple (abyssal) and complex (mid-ocean ridge) sites are presented in Fig. 6, with the following set of explanatory notes:

- Decision 'Is the site close to abrupt topography': When flow is tidally-dominated, topographic flow features are not expected to be apparent more than a tidal excursion downstream (the tidal excursion is the distance over which water is transported back and forth during a tidal cycle), so can essentially be considered to be locked over the topography. In more persistent flows, effects may be apparent further downstream; while this distance is dependent on the flow regime, and detailed observations of such processes are rare or non-existent, a rule of thumb of 10 km or 5 times the length scale of the topography is suggested as a reasonable threshold for proximity, subject to revision as knowledge improves.
- Decision 'Tides>>Eddies': Do tidal currents dominate low frequency currents (i.e. the background mean flow and eddies that may penetrate to the depth of the plume), or vice versa? Tides are relatively predictable, whereas eddies and other low frequency variability may appear somewhat random when viewed from a single point. A long (1+ year) time series of currents is needed to provide a realistic assessment of the role of eddies and to identify extreme current events for this site. High surface EKE would also suggest that deeper variability in low frequency flows is likely, although this should ideally be supported by direct current observations.

- Outcome 'A': [A tidally-dominate abyssal site far from topographic features]. This is perhaps the least complex type of site. Tidal flow is not expected to be especially strong in deep water away from topography. Turbulence is expected to be relatively weak. A plume is expected to be relatively not very extensive, vertically or horizontally, but near-field impact would be greater than in more dispersive environments.
- Outcome 'B': [An abyssal site far from topographic features where background flow and eddy variability may be significant]. In comparison with 'A', still a site of relatively low complexity, but with the potential for greater downstream transport of plume material, and a less predictable pattern of impact (e.g. with variable 'rays' of impact, as in Fig. 3).
- Outcome 'C': [A tidally-dominate close to abrupt topography]. Similar to 'A' except that intense vertical mixing is possible over or close to the topographic feature. This is unlikely to influence the plume from mining operations nearby, as tidal excursions are typically small in the deep sea (hundreds of metres), so would not transport plume material over the feature.
- Outcome 'D': [A site close to abrupt topography where background flow and eddy variability may be significant]. Similar to 'B' except that intense vertical mixing is possible over the topographic feature or in adjacent flat areas (lee waves or hydraulic jumps). So, plumes could be mixed rapidly vertically if the mining operation passes through such a mixing patch, or plume could be advected towards the topographic feature and entrained into such a patch. The plume may then become vertically extensive (e.g. hundreds of metres) and transport further before settling, increasing far-field impact.
- Outcome 'E': [A bathymetrically complex, tidally-dominated site with much steep topography]. This is the most complex type of site. Much tidally generated turbulence is expected in the boundary layer of steep slopes and in the adjoining water column. Plumes will become vertically extensive (hundreds of metres). Other complex flow structures such as bores and gravity currents may drive plume material away from the bed into the water column. Plume patterns will be highly sensitive to local factors and spatially variable. (An example of such a site is described by Dale and Inall, 2015)

- Outcome ‘F’: [A bathymetrically complex, tidally-dominated site with less steep topography than ‘E’]. In comparison with ‘E’, the water column is expected to be less turbulent so the plume would be less vertically extensive, however it would be expected to be highly three-dimensional in response to local topographically-steered flow patterns.
- Outcome ‘G’: [A bathymetrically complex, site where low frequency flows dominate]. Many bathymetrically complex sites have dominant low frequency flows driven by local mixing. In such cases, hydraulic flows over topography may generate intense downstream mixing patches. The relatively slowly-varying conditions mean that plume transport can be extensive and aided by vertical mixing drawing material up into the water column (hundreds of metres). (An example of such a site is described by St Laurent and Thurnherr, 2007).

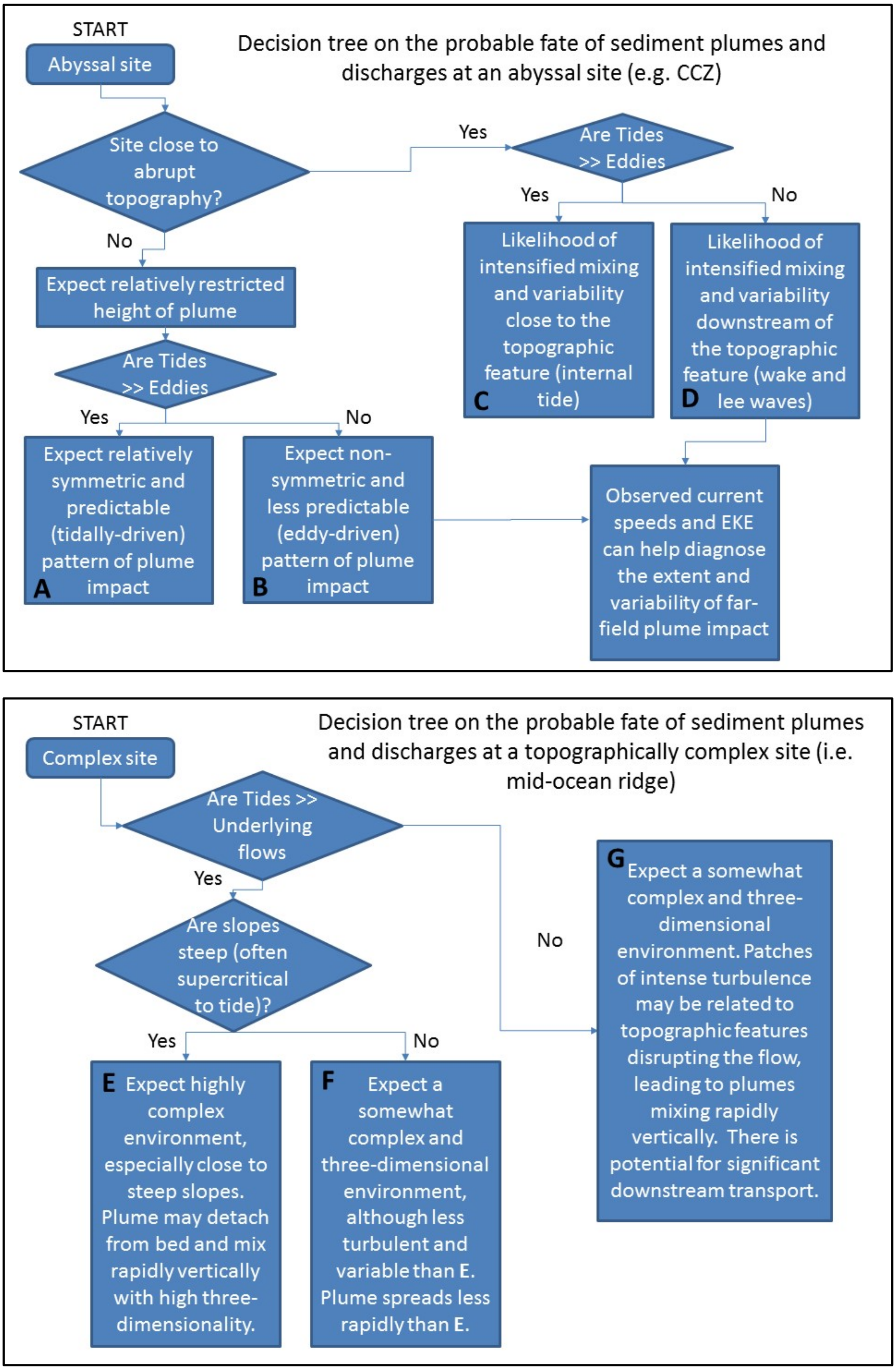

Figure 6. *'Decision trees' for abyssal and complex (i.e. mid-ocean ridge) sites*

5. Comments regarding hydrodynamic modelling of plume environments

The differing hydrodynamic environments and the plume behaviour expected in these environments have a major bearing on the selection of appropriate hydrodynamic modelling approaches, so it is appropriate to discuss this aspect here in relation to the decision tree.

The key decisions to be made with respect to hydrodynamic modelling approaches are:

- Model resolution (i.e. the spacing of the model computation grid or mesh)
- Level of model dynamics (in particular, whether a computationally expensive non-hydrostatic model is needed to adequately represent the dynamics of the site)
- Model extent and boundary forcing

Underlying this decision-making process is the understanding that hydrodynamic modelling of the deep sea across the broad range of scales that are relevant to plumes is not possible at the level of detail that might be desired. In complex mid-ocean ridge environments, three-dimensional hydrodynamic models are not close to converging as resolution is improved (Zilberman et al., 2009) because the relevant dynamical scales are too small (Dale and Inall, 2015) to resolve in three dimensions with existing computational resources. The models that best represent flow-topography interaction in the deep sea have resorted to two-dimensional approximations (Klymak et al., 2010; Legg and Huijts, 2006), however the dynamical processes that such high-resolution models are able to represent would be hugely important in understanding the fate of plumes in the vicinity of steep slopes in mid-ocean ridge environments.

Discussing the site categorisations of the decision tree:

Abyssal site A: The simplest abyssal sites, without significant nearby topographic influences, can arguably be best represented in a plume model by directly using observed velocities (e.g. from a mooring) and assuming that they are spatially uniform. This approach yielded the results described in section 2, and does not require a hydrodynamic model. The loss of any spatial structure to the flow pattern is compensated by the accurate representation of temporal patterns in the observed time series. Without nearby sources of complexity it is likely that much of the flow field is in fact relatively spatially uniform, and any non-uniformity would be difficult to represent in a model.

Abyssal site B: An eddy resolving model is clearly required to represent the role of low-frequency flow variability. This requires either a large scale approach that assimilates eddy-resolving observational data (e.g. surface altimetry), or nesting within such a model (e.g the globally-available HYCOM).

Abyssal sites C and D: The modelling approach for sites of type B would not represent adequately the effects of abrupt topography. If these effects are considered important, a high-resolution and ideally non-hydrostatic approach is recommended, although the provision of eddy resolving boundary forcing is problematic and would involve nesting within a regional model.

Complex site E: To adequately represent the most complex tidally-dominated mid-ocean ridge environments requires resolution of the tidal excursion, ideally resolving sub-100 m scales, and the use of a computationally expensive non-hydrostatic model. Accurate bottom slopes are also important, so multibeam bathymetry is essential. These requirements are only computationally feasible in very small domains at present. Regional simulations at reduced resolution may be adequate in the mid- to far-field but are unlikely to accurately predict impacts within hundreds of metres and kilometres of a mining site.

Complex sites F and G: Sites of these types will show somewhat reduced complexity that type E. Conceivably, lower resolutions could be used and a hydrostatic model may be appropriate with the caveat that the most turbulent locations would not be well represented. For accurate representation of the near-field of a mining site, however, a high-resolution non-hydrostatic model is still recommended.

6. Summary

A broad metric-based decision tree has been presented for distinguishing between hydrodynamically differing mining sites as an aid to inferring the likely nature of mining plumes. Of course, the ocean is a complex and highly variable environment, the nature of which cannot be perfectly distilled into a set of metrics. For this reason, all metric-based evaluations or decisions must be followed by a 'sanity check' to ensure that the outcome appear reasonable in the light of available knowledge and experience. This applies especially when evaluating a site that differs in some respects from the typical mining sites that have been considered here (abyssal nodule sites and mid-ocean ridge sites). In particular, sites where these decision making tools should be treated with caution include: high latitude sites (Arctic/Antarctic), shallow water sites, sites near continental slopes, deep (hadal) trenches, since such sites have their own characteristic physical processes which will influence plume behaviour.

The outcomes of the decision tree largely relate to the relative role played by tides and low frequency currents (mean background and eddying components), and the steepness and proximity of topographic features. These factors control the predictability of the flow environment and the likely presence and distribution of patches of intensified turbulence. A simple study of the role of turbulence and current speed on plume predictions shows that the influence of these factors on plume impacts is highly sensitive to the exact metrics of impact chosen, and it is extremely important that these are clarified with respect to ecological impacts in the deep sea.

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Appendix A: Modelling of a nodule mining plume in a realistic scenario

The plume simulations presented in section 2 are based on a realistic nodule mining scenario developed by Kevin Murphy (ERM) under MIDAS WP7 through consultation with industry.

In this scenario it is assumed that a single nodule collecting machine has a collector width of 15 m, and makes forward progress at 0.3 ms^{-1}. In harvesting the nodules, the top 15 cm of sediment is removed and 90% of this material is released from an exhaust at the rear of the vehicle. Here it has been assumed that the wake of the vehicle mixes this exhaust evenly through the bottom 4 m of the water column. The vehicle covers the seabed in a 'lawn mowing pattern of multiple adjacent strips, covering 100% of a 12 km square region of the seabed in the course of a year.

The particle size distribution of the ambient sediment has been taken from measurements provided by Dan Jones (NOC) from a site in the CCZ (James Cook cruise JC120), and sinking speeds are determined by standard approaches for spherical sediment particles without accounting for flocculation or scavenging.

Particles are subject to transport by a current, based on a near-bed time-series from the German claim in the CCZ provided by Annemiek Vink (BGR), and have also been subject to eddy diffusion with constant diffusion coefficients in the vertical and horizontal directions.