MIDAS

MANAGING IMPACTS OF DEEP SEA RESOURCE EXPLOITATION

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Report on the effects of a range of characteristic hydrodynamic regimes on the three discharge methodologies in terms of near-field dilution

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1. Introduction

The initial behaviour of a discharge plume depends on the discharge methodology, the processes involved in equilibration of the plume with ambient water, and the hydrodynamic nature of the site in question. Here we consider the latter, the influence of the hydrodynamic nature of the site, and consider the extent to which sites can be characterised in terms of their hydrodynamic properties. Such characterisations would potentially allow some level of prediction of behaviour at sites for which hydrodynamic observations are either limited or not available.

The focus here is on the near-field of the plume, defined as sub-kilometre scales, within tens to hundreds of metres of the source, and the lower part of the water column. The near-bottom environment is of particular interest. Three discharge methodologies are considered, and these are detailed in Table 1.

Type of discharge	***Location of discharge***	***Nature of material***
A) Dissolution and resuspension from tailings deposited on the seabed.	Seabed	Soluble and fine material, with an upper size limit imposed by the current speed.
B) Pumped, and potentially buoyant, discharge of dissolved and suspended materials from a pipe sited at depth.	Lower water column	Wide range of particle sizes possible, according to nature of the material and processing involved.
C) Direct mechanical disturbance of the seabed.	Seabed	Size range of particles represents the local in situ sediment.

Table 1. *The three types of discharge under consideration, and the nature of the material entering the water column.*

In essence, these discharges will be considered to consist of a localised source of material which may be instantaneous, or ongoing, and may be at a fixed, or moving, location.

At the simplest level, the initial behaviour of a plume can be considered as an advective-diffusive process, in which material is transported by ambient currents and mixed diffusively with surrounding water. Diffusion typically acts several orders of magnitude faster horizontally than vertically, reflecting the differing scales of the ocean and the constraining influence of stratification in the vertical. At all but the smallest scales (order centimetres), diffusion is principally achieved by stirring motions which are both time-varying and potentially three-dimensional. In applying an advective-diffusive model there is an implied assumption that the length and time scales of interest with respect to the plume sit between much longer advective scales and the much shorter turbulent scales that lead to diffusion. In reality this scale separation is frequently not distinct, meaning that a plume evolves in a considerably more complex manner, directly distorted by turbulent stirrings and process-level physics.

This report considers the deep-sea environment, both in general terms (current speeds, stratification, turbulence and mixing), and at the process level. It also aims to highlight the considerable uncertainties that exist as a result of the scarcity of high quality observations that resolve small-scale physical processes in the deep sea.

For simplicity, the principal focus is on two types of deep-sea environment that are of potential mining interest (Figure 1):

1) Mid-ocean ridge environments, with considerable topographic complexity, often with an axial canyon at their spreading centre and transverse canyons on their flanks.

2) Relatively flat abyssal plains with isolated and abrupt topographic features (typical, for instance, of the Clarion-Clipperton Zone in the Pacific).

Together, these sites comprise much of the global seafloor, with mid-ocean ridge environments alone accounting for 33% (Heezen, 1969).

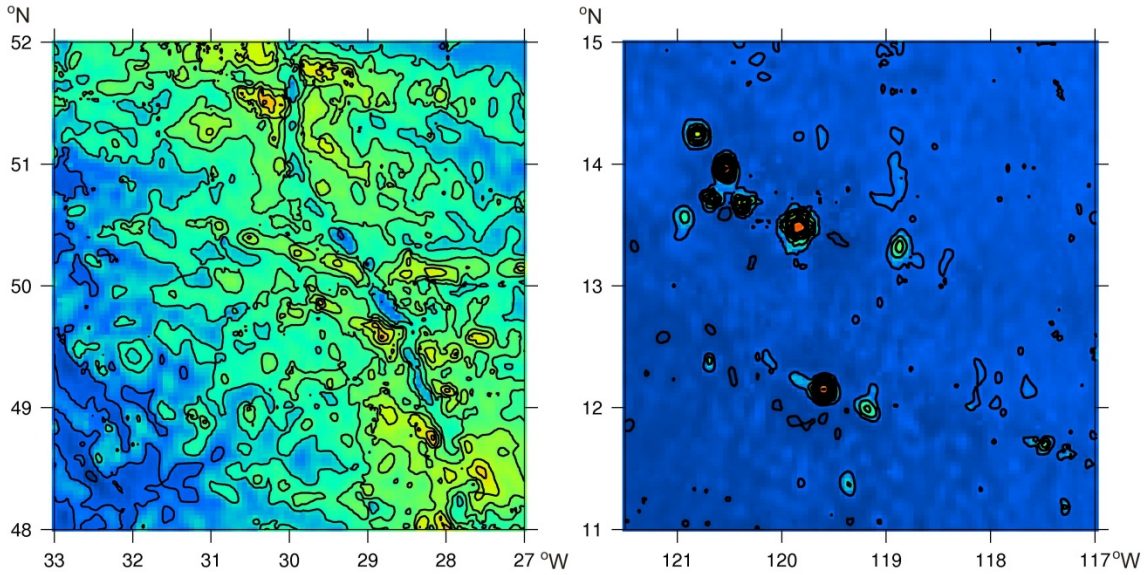

Figure 1. *Two contrasting deep sea topographies from (a) the Mid-Atlantic Ridge and (b) the Clarion-Clipperton Zone of the Pacific. These figures are based on satellite derived data, resolving scales of 25 km and above (Smith and Sandwell, 1997). The contour interval is 500 m. Each extract covers approximately 440 km x 440 km.*

2. The hydrodynamic character of the deep sea

2.1 Overview of currents, stratification, turbulence and mixing

The deep sea hydrodynamic environment differs from environments near the surface or in shallow water in several important respects. The key difference stems from the fact that the majority of ocean forcing occurs at the sea surface. This includes direct mechanical forcing by wind stress, as well as indirect forcing by buoyancy (evaporation, precipitation) or heat and radiative fluxes to and from the atmosphere, which modify near surface density structure. Combined with this is the differing nature of the free, and relatively flat, sea surface boundary, compared to the rigid bathymetric bottom boundary experienced by deep flows.

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; Turnewitsch et al., 2013) (although this large dataset may have bias toward energetic areas). Low frequency flows, those that vary over a time scale of days or longer, have a tendency to follow contours of bottom depth, but this tendency is reduced with height above the bed due to the presence of stratification, so surface flows are relatively unconstrained by underlying topography and may eddy freely. In contrast, deep flows are strongly steered by topography. This means that topographic complexity is reflected in the spatial complexity of deep flows (Xu et al., 2010), so although spatial complexity exists at all levels in the ocean, deep flows are frequently less temporally variable, being relatively more locked to topography. Variability due to upper ocean eddies may in some regions penetrate to full ocean depths, however. At no level can local currents be expected to reflect the large scale circulation patterns that are evident in distributions of hydrological characteristics (Kontar and Sokov, 1994).

In addition to large scale flows and their inherent structure and variability, residual flows at depth may also be driven locally by mixing and subsequent readjustment of density structure. Boundary mixing on a slope drives a compensating upslope flow against the boundary (Phillips et al., 1986), a process that is most significant in areas of complex bathymetry and significant boundary mixing, such as mid-ocean ridges, and is responsible for the dominant flows along the axis of abyssal canyons (St Laurent et al., 2001; Thurnherr et al., 2002).

The relatively weak stratification of the deep sea means that the natural horizontal scale of flow structures, the baroclinic Rossby radius, is shorter than in the upper ocean. Vertical scales tend to be larger since the energy required to move vertically against stratification is less. This narrowing of the difference between vertical and horizontal scales means that deep flow structures are more three-dimensional. It also means that the deep sea is often highly turbulent, despite having relatively low energy levels, since less energy is required to overturn and mix a weakly stratified water column. In the context of plumes, this means that diffusive spreading in the vertical may be rapid.

2.2 Challenges of observing processes in the deep sea

Process-resolving observations of the deep sea are few. The observation of complex, three-dimensional and time-evolving flow structures in shallow water is challenging, but the difficulties are compounded in the deep sea by the technical difficulties and time involved in deploying and recovering instrumentation. Additional difficulty arises from the relatively smaller horizontal scales and the problem of accurately positioning instruments which are deployed by free-fall from a vessel above.

The most comprehensive process-level observations to date are therefore of flow structures with relatively long time and length scales, such as the topographic effects on flows within canyons (St Laurent and Thurnherr, 2007; Thurnherr et al., 2005), or abyssal channels (Alford et al., 2013; MacKinnon et al., 2008). High-frequency (e.g. tidal) processes are more difficult to resolve, so process-level understanding is largely based on high resolution modelling studies (Klymak et al., 2010b; Legg and Huijts, 2006) supplemented by observations made simultaneously at nearby locations which hint at processes and underlying complexity (Dale and Inall, 2015). Single point moorings provide some information concerning processes (e.g. Thorpe, 1983), but lack horizontal context. Further detail is contained in the sections that follow.

3. Processes

3.1 Synoptic variability and benthic storms

Periods of elevated currents at abyssal sites have been termed 'benthic storms' in the literature. These events are not the result of atmospheric storms, but result from penetration to the seabed of variable or moving geostrophic flow structures from higher in the water column. This includes the meandering of jets, the passage of eddies and density currents cascading down adjacent continental slopes. Clearly, periods of elevated flow have implications for the behaviour of active mining plumes, but they also raise the likelihood of resuspension and redistribution of previously settled material or of natural sediment (Hollister and McCave, 1984; Laine et al., 1994; Richardson et al., 1993).

The most dramatic events of this sort have been observed in the vicinity of intense surface boundary currents. The HEBBLE site, at a depth of 4800 m on the continental rise off Nova Scotia lies beneath the meandering northern flank of the Gulf Stream, at a depth where the mean flow is reversed (equatorward). Benthic storms in this location have been defined as daily-averaged currents exceeding 15 cm s^{-1} for two or more consecutive days (Weatherly and Kelley, 1985) (note that the 73 cm s^{-1} reported by Richardson *et al*., 1981, was erroneous). Individual 'storms' occur every 1-3 months, leading to dramatic changes in the character of the seafloor (Hollister and McCave, 1984) and increased near-bed turbidity representing long-distance transport of fine material. The occurrence of such storms at this site has been linked to the presence or absence of Gulf Stream meanders and eddies at the surface (Kelley et al., 1982; Weatherly and Kelley, 1985). The surface expression of meanders and eddies of this type can be routinely identified via satellite altimetry, though their expression at depth cannot necessarily be inferred.

That said, abyssal flow variability at other sites, as measured by eddy kinetic energy, has a similar tendency to be greatest beneath areas of high eddy kinetic energy at the surface including beneath intense boundary currents, such as the Gulf Stream (Schmitz, 1984a), the Kuroshio (Schmitz, 1984b), the Agulhas retroflection (Cronin et al., 2013), and the Brazil Current (Richardson et al., 1993). These areas of high abyssal eddy kinetic energy also tend to experience benthic storms. Penetration of surface flow features and variability has also been observed in open ocean locations (i.e. remote from intense boundary currents), however, and the term 'benthic storm' has similarly been applied. Whenever current speeds are elevated above background levels they will tend to erode material deposited under less energetic conditions. The Clarion-Clipperton zone of the NE equatorial Pacific is an open ocean region of relatively high surface eddy kinetic energy. A 10-day period of elevated currents was observed 6 m above the bed at a depth of 4920 m, associated with the passage of a surface-intensified anticyclonic eddy, with current speeds raised from the 2-6 cm s^{-1} background level to a peak of 13 cm s^{-1} (Demidova et al., 1993; Kontar and Sokov, 1994).

3.2 The benthic boundary layer

A steady flow over a flat bottom is retarded by friction, leading to a sheared boundary layer which becomes, at least intermittently, turbulent (D'Asaro, 1982). In a one-dimensional approximation, a mixed layer develops with a thickness that reaches approximately

$$H = 0.1U(fN)^{-1/2} ,$$

where U is the external current speed, f is the Coriolis parameter, and N is the ambient buoyancy frequency (Richards, 1990). This picture is complicated when overlying flows redistribute mixed layer fluid and drive an Ekman transport within the bottom boundary layer at right angles to the overlying flow. Convergences or divergences of this Ekman transport result when eddies in the overlying flow

penetrate to the seafloor and lead to thickening or thinning of the boundary layer (Armi and Dasaro, 1980; Richards, 1990) (Figure 2d). On slopes there are additional buoyancy effects, whereby a downslope Ekman transport destabilises and thickens the boundary layer, whereas an upslope Ekman transport stabilises and thins it (Middleton and Ramsden, 1996; Trowbridge and Lentz, 1991). Bottom mixed layer depths in the abyssal ocean therefore cover a wide range, around 5-100 m (Kontar and Sokov, 1997). Plume material would be expected to disperse rapidly vertically within the mixed layer, but the sharp density gradient at its upper boundary would supress exchange with the adjoining water column.

While a benthic mixed layer is vertically homogeneous it may have horizontal gradients and structure. Even above a relatively flat abyssal plain, lateral gradients may take the form of sharp fronts (Thorpe, 1983). On the Madeira Abyssal Plain, at a depth of 5293 m these fronts were found to extend for at least 8 km horizontally, having a cross-front scale of a few hundred metres and a temperature difference of $2\text{-}4\times10^{-3}$ °C. A front provides a route by which fluid (and material suspended within it) can escape from the boundary layer, travelling along a density surface into the interior of the stratified water column (Figure 2a) (Richards, 1990). While the potential for such boundary layer escape is greater on a slope (Inall, 2009; McPhee-Shaw, 2006) (Figure 2c), since even horizontal density levels will intersect the top of the boundary layer, the existence of fronts in flatter abyssal regions suggests that boundary layer escape is also possible in these locations.

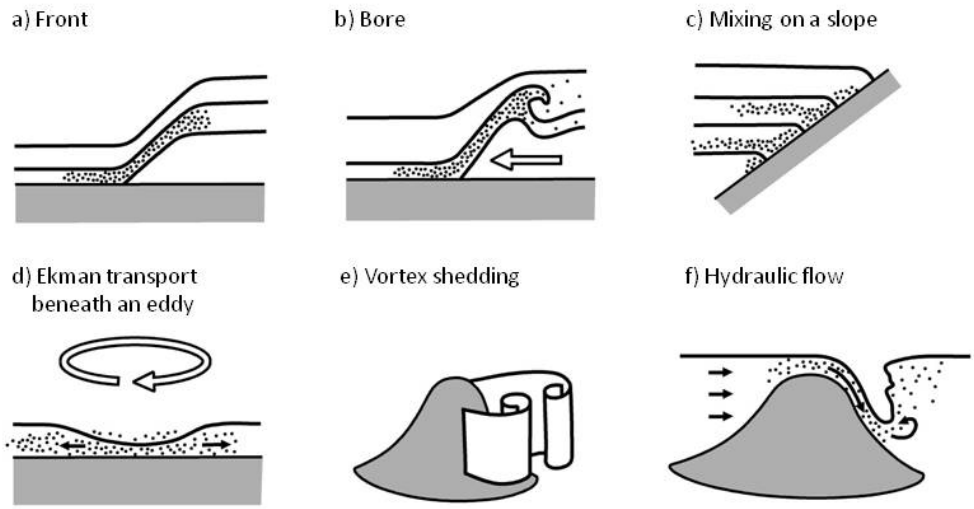

Figure 2. *Processes that can lead to boundary fluid escaping from the bottom boundary layer and entering the stratified water column (based in part on Richards, 1990).*

3.3 Interactions between steady flow and isolated topographic features

Interaction between ambient flow and topographic features can produce a rather complex range of phenomena. These will be summarised here, although more detailed reviews consider these interactions in far greater detail (Baines, 1995; Chapman and Haidvogel, 1992; Turnewitsch et al., 2013). Tidal periodicity adds further complexity (see 3.6).

Topographic features frequently appear as isolated hills or seamounts in otherwise flat abyssal areas (there are many millions of such features; Wessel et al., 2010), or they may combine into extensive tracts of complex, multi-scale topography, such as at mid-ocean ridges. In the simplest case, of an isolated hill or seamount, the parameters governing its interaction with a steady flow are the ambient

velocity U, the height h and horizontal scale L of the topography, the total water depth H, the level of stratification (buoyancy frequency) N, and the Coriolis parameter f, representing the role of the Earth's rotation (which depends on geographic latitude). These scales can be distilled into a set of dimensionless parameters, the Burger number, $S = \frac{NH}{fL}$, representing the relative influence on the flow of stratification versus the Earth's rotation, the Rossby number $Ro = \frac{U}{fL}$, representing the strength of the background flow, the fractional height of the seamount $\delta = \frac{h}{H}$, and the aspect ratio $\frac{H}{L}$.

As described previously, steady flow has a tendency not to cross depth contours, as a result of the Earth's rotation. This means that fluid above the summit of an isolated hill or seamount may be retained in that location, with nearby flow parting around it. This tendency is lessened by stratification (large Burger No. S), when the retained area of fluid reduces with height (forming a 'Taylor cap'), or in strong flows or for small topographic features (large Ro or small δ) (Chapman and Haidvogel, 1992; Hogg, 1973).

The compression of the water column when flow encounters a seamount induces vorticity and leads to asymmetry in the flow. In the Northern (Southern) Hemisphere, currents are enhanced on the left (right) flank of the feature, looking downstream, and diminished on the right (left) flank (Gould et al., 1981). From the perspective of mining discharges, fluid retention within a Taylor cap would lead to weak dispersion of material released within the cap itself. Conversely, material in suspension near to a seamount would not be expected to impact its summit if a cap exists.

Downstream of the topographic feature, flow may smoothly converge, form a steady wake, or create an oscillating wake in which eddies of alternating sign are shed downstream (Boyer et al., 1987) (Figure 2e). The presence of strong stratification allows the establishment of eddy shedding at lower velocities than would otherwise be the case, by supressing flow over the summit. In conditions in which a Taylor cap does not form, and flow passes over a feature, the vertical displacement of density structure creates internal waves. For topographic Froude number $Nh/U \geq 1$ internal waves are stalled downstream as lee waves and blocking of the upstream flow occurs (Klymak et al., 2010b). For $Nh/U \approx 1$ a hydraulic transition occurs over the summit. Flow accelerates into an intense downslope flow ending in a turbulent hydraulic jump at which fluid decelerates rapidly, mixes and separates from the boundary (Figure 2f). Hydraulic flows of this sort have been observed over sills in abyssal canyons (St Laurent and Thurnherr, 2007; Thurnherr, 2006), associated with enhanced mixing.

3.4 Barotropic tides

The barotropic tide is the depth-averaged flow that results from astronomical tide generating forces and the consequent changes in sea surface elevation. In distorting the oceans and driving currents, some of the energy imparted to the ocean is dissipated, primarily through the interaction between tidal currents and the seabed. Satellite altimetry provides accurate measurement of the elevation of the ocean surface which permits high quality global models of the barotropic tide (Egbert and Erofeeva, 2002). This also enables the global distribution of energy loss from the barotropic tide to be mapped (Egbert and Ray, 2001). Since barotropic tidal currents are small, relatively little energy is lost by direct friction with the seafloor. A more significant energy loss occurs as currents on a sloping seabed generate an internal tide.

3.5 Interaction between tides and slopes – the internal tide and slope criticality

Tidal flows with a cross-slope component move density structure vertically, doing work against stratification. This radiates internal waves into the surrounding water column and produces a variety of local internal phenomena.

Internal wave energy travels along inclined ray paths, the slope of which,

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

depends on the wave frequency σ, the ambient stratification N, and geographic latitude via the Coriolis parameter f. Motion of water parcels is along these paths, the inclination of which is generally only a few degrees from horizontal. When tidal flow interacts with a sloping seabed, the response differs greatly depending on whether the slope is less steep than ray paths at the tidal frequency (a sub-critical slope), of similar steepness (a critical slope) or steeper than the ray paths (a super-critical slope). When slopes are near-critical, high energy densities may occur near the bed, associated with strongly sheared and often turbulent flow (Gayen and Sarkar, 2010; Moum et al., 2002). Super-critical slopes are also more efficient at extracting energy from the barotropic tide than sub-critical slopes of similar vertical extent (Klymak et al., 2010a; St Laurent et al., 2003). Critical slopes are believed to experience enhanced erosion, leading to the development of intermediate nepheloid layers in the adjoining water column (Moum et al., 2002; Thorpe and White, 1988), and have even been implicated in controlling the gradient of continental slopes (Cacchione et al., 2002), emphasising the potential role of their intensified and turbulent flow in eroding, or resuspending, and transporting bed material.

3.6 Internal bores

Internal bores (Figure 2b, 3) have been observed on the flanks of large seamounts, at the foot of the continental slope and in complex mid-ocean environments (Aucan et al., 2006; Dale and Inall, 2015; Hosegood and van Haren, 2004; Van Haren, 2005; Van Haren et al., 2005), suggesting that they are widely distributed in the deep ocean. There is strong evidence that these bores are tidal in origin, occurring once per tidal cycle, although they rapidly lose their tidal phasing as they propagate away from generation sites (Dale and Inall, 2015). In their structure these features resemble gravity currents, consisting of a density interface that intersects the bed and is driven forward (in the direction of the less dense water) by the resulting lateral pressure gradient. The propagation is typically upslope. The front is followed by an elevated turbulent head and a trailing layer of dense fluid, typically of tens to a hundred metres thick, with shear and turbulence on its upper boundary. Current speeds may increase during the passage of such a feature. Material within the water column near the seabed is lifted over the head of the advancing front, and mixed in its lee, so there are significant implications for plumes near the seafloor or for existing settled tailings. The mechanism responsible for internal bores is unclear. Model simulations suggest that a critical slope is important for bore formation (Gayen and Sarkar, 2011) however they have also been observed in non-critical situations. Bores may also result from externally generated internal waves impinging on a slope (Hosegood and van Haren, 2004), so sites must be considered in the context of adjoining slopes and features.

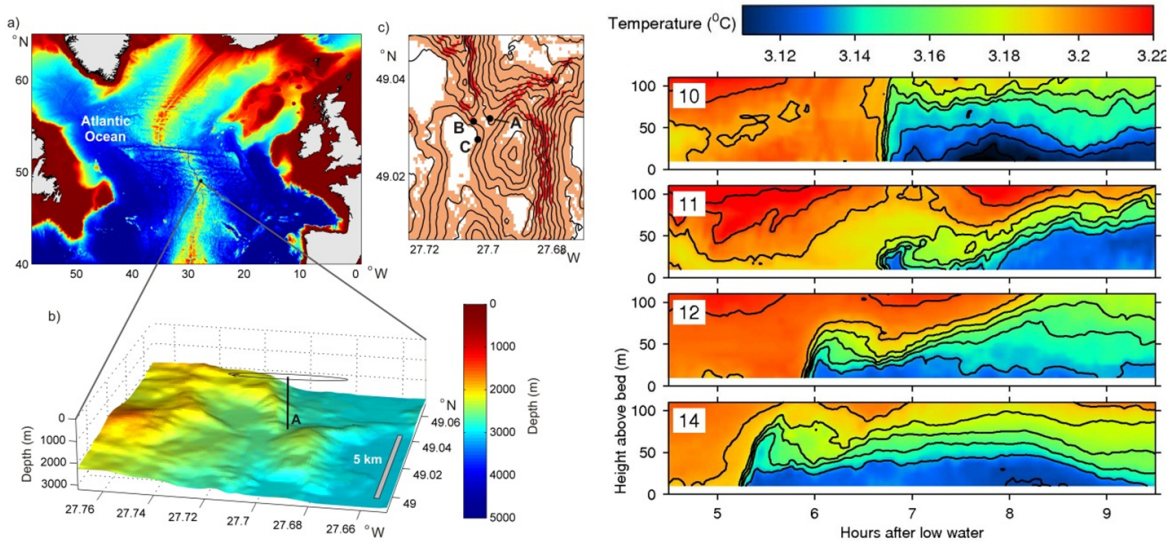

Figure 3. *Tidally pulsed overflows of relatively cool, dense water observed at a saddle, the low point of a ridge, among complex mid-ocean ridge topography (Dale and Inall, 2015).*

3.7 Interactions between tides and isolated topographic features – hydraulics and lee waves

For an isolated topographic feature, the processes governing tide-topography interaction are as described for a steady flow (3.3) with the additional influence of slope criticality and the horizontal scale of the topography relative to the tidal excursion (Garrett and Kunze, 2007). The complexity of the situation is compounded if there is non-tidal flow or three-dimensionality of background flows or topography.

When topographic scales are large compared to the tidal excursion, individual water parcels experience the topography as a slope, so this is the case described in 3.5. When topography contains scales that are comparable to or shorter than the tidal excursion, water parcels experience changes of gradient, permitting processes such as lee waves, hydraulically-controlled flows and overflows. This case includes changes of gradient on the slopes of larger features (Klymak et al., 2008; Legg and Klymak, 2008), as well as topographic features that are themselves comparable to the tidal excursion scale. While several studies have considered tidal interactions with excursion-scale topography from a modelling perspective (Legg and Huijts, 2006; Nikurashin and Legg, 2011), detailed observations have been lacking. From the perspective of mining plumes, the most significant cases are likely to be those in which the tidal flow speed stalls internal waves generated by flow across the sloping bed. As described in 3.3, when $Nh/U \approx 1$, intense downslope flow develops in such cases on the lee side of topographic features, terminating in a turbulent hydraulic jump. The added tidal variability means that this jump may propagate upslope as a bore when the tide turns and similar features may then develop on the opposite flank of the feature.

3.8 Other processes

The preceding sections have summarised some of the principal elements of near bed flow dynamics, but this is clearly a complex field. Any attempt to divide ocean dynamics into component processes and structures is necessarily simplistic. The ocean is a, frequently turbulent, multi-scale fluid in which

energy is imparted by forcing, is transferred between scales and is dissipated in a highly non-linear manner. Superimposed and interacting with the processes described above is considerable background variability, representing local turbulence, the oceanic internal wave field (Garrett and Munk, 1979; Levine, 2002), as well as rapidly-evolving and difficult-to-categorise dynamics at the sub-mesoscale (kilometres).

4. Characterising the behaviour of a mining plume in differing environments

4.1 Plume dynamics

As described in the introduction, the behaviour of a mining discharge, or suspension from the bed, is at its simplest level an advective-diffusive problem, with an extra dimension provided by its distortion by flow structures that have similar length and time scales to the plume evolution.

A mining discharge can be considered to consist of particles of a range of sizes and potentially a dissolved component. Particle sinking rates depend on their size, density and other characteristics, such as their shape, or their tendency to clump together into a floc (Maggi, 2013). The fastest-sinking (typically largest) particles will be minimally affected by currents or turbulence. It is the smaller particles and dissolved material, with sinking speeds that are comparable to or slower than expected vertical current speeds, that will be most affected by the hydrodynamic character of the site. The vertical currents of interest include those related to turbulent overturns which are responsible for vertical (eddy) diffusion, since diffusive fluxes may dominate settling fluxes.

When a discharge enters the water column, or is suspended from the bed, it will contain a range of particle sizes. The larger, more rapidly-sinking particles will reach the bed first, while finer particles will travel further in the greater time that they are suspended within the water column. The size spectrum of material, both in suspension within the plume and settled on the seabed, will therefore become increasingly skewed towards the finer particles with distance (and time) from the origin.

For a given quantity of material discharged into the water column, or disturbed from the bed, more energetic and diffusive environments will tend to retard the settling of the plume and it will be transported further during the time that it is within the water column. The water column concentrations of material will be lower than in a less diffusive case, and settled sediment thicknesses will be less. These reduced impacts will clearly be more widely spread. The assessment of impact of the plume therefore hangs on the relative importance of the spatial extent of the impact and the magnitude of the impact. Understanding the local hydrodynamic situation may also provide information on the likely pathway of plume material and sites of deposition.

Type	Source	Notes/description
General circulation model	HYCOM (http://hycom.org)	1/12° global data assimilative runs available in hindcast mode.
Barotropic tidal model	TPXO global tidal solutions (Egbert and Erofeeva, 2002) (http://volkov.oce.orst.edu/tides/)	1/4° global model of the barotropic tide (depth mean tidal currents).
Altimetry	AVISO (http://www.aviso.altimetry.fr/)	Satellite altimetry. Provides information on surface currents and eddy kinetic energy.
Bathymetry	Smith and Sandwell Global Topography (http://topex.ucsd.edu/marine_topo/)	1-minute global bathymetry from satellite and ship-based data (resolves scales >25 km).
Climatology of density structure	NOAA World Ocean Atlas (https://www.nodc.noaa.gov/OC5/woa13/)	1/4° global climatology of temperature, salinity etc. at standard depths.

Table 2. *Examples of readily available global datasets of potential use for hydrodynamic characterisation of sites of mining discharges. These listings are illustrative and are not intended to be comprehensive.*

4.2 What information is required to characterise plume behaviour at a given site?

Given the complexity of ocean dynamics, the lack of thorough understanding of deep-sea flow processes, and the range of environments in which mining operations may occur, characterisation of sites appears to be a challenging objective. The requirement is to have some understanding of typical background flows, including the variability of these flows, as well as estimates of the associated rates of vertical and horizontal turbulent diffusion. In addition, it is important to identify the physical processes that may be encountered at a particular site, and in particular those that will lead to increased turbulence or current speeds, or ejections of material from the benthic boundary layer into the adjoining water column.

As described in the previous section, many physical processes can be predicted to some extent on the basis of geographical location, the magnitude of ambient and tidal flows, the proximity to energetic or variable surface features, and the nature of the local topography. Site characterisation therefore needs access to either detailed local observations of these aspects, or adequate datasets from which they can be derived. Table 2 gives examples of high quality and freely available global datasets that are useful for site characterisation. These all suffer to some extent from the lack of spatial resolution that is unavoidable in global datasets, and this will be discussed further in 5.1.

The following sections discuss the quality of global circulation models as a source of information on the currents, and knowledge of the distribution and variability of turbulent diffusion.

4.3 How well do global circulation models represent currents in the lower water column?

Global ocean circulation models are continually improving in their resolution and in their ability to assimilate observational datasets. The assimilation of surface altimetry data from satellites allows

eddy-resolving models to retain accuracy in their representation of surface geostrophic currents at mesoscales and above, however, deeper within the water column, useful data sources are increasingly sparse. Temperature and salinity profiles from ARGO floats provide extensive global coverage but they are not, in general, eddy-resolving, they do not extend to full oceanic depths, and they do not directly measure currents. Deep in the water column, models rely increasingly on their own simulated dynamics, including the parameterisations of mixing processes which exert an strong influence on predicted circulation (Hasumi and Suginohara, 1999; Jayne, 2009). There is also evidence that a finer resolution is required to represent deep water flow structures than those near the surface (Penduff et al., 2006).

A number of studies have looked at the performance of global circulation models with respect to independent current meter datasets (i.e. datasets that have not been assimilated into the model solutions themselves) (Arbic et al., 2009; Penduff et al., 2006; Scott et al., 2010). As expected, there is a tendency for model performance to become poorer with depth, with deep kinetic energy *underestimated* in many models as currents speeds reduce too rapidly from more realistic levels at the surface. In the most extensive comparison, between more than 5000 current meter datasets and the performance of 4 different global models at 1/10° to 1/12° resolution (Scott et al., 2010), the best performance was by a data-assimilative version of HYCOM. Concerns were raised regarding the parameterisation of bed friction in some models, leading to overly-damped near-bed flows, and also regarding the very considerable scatter in model-data comparisons. It appears that model predictions cannot be assumed to be reliable at individual, arbitrarily chosen sites (Scott et al., 2010). Although global models are clearly still somewhat deficient in their simulation of abyssal flows, and should currently be used with caution, they will surely improve and become a more useful tool for categorising the hydrographic nature of arbitrarily located deep-sea mining sites.

4.4 Vertical diffusivity

The rate of diffusive spreading of a patch of dissolved or suspended material is most simply described by an (eddy) diffusion coefficient, or diffusivity. This assumes that diffusive fluxes of the substance of interest are proportional to its concentration gradient (Fick's Law), expressed in the vertical direction as

$$F_z = -K_z \frac{\partial c}{\partial z},$$

where F_z is the flux in the vertical (z) direction, K_z is the diffusivity, and $\frac{\partial c}{\partial z}$ is the component of the concentration gradient in this direction. In the ocean, vertical diffusion is typically several orders of magnitude less rapid than horizontal diffusion because of the spatial constraint imposed on turbulent motions (the aspect ratio of an ocean basin is ~1:1000), and the presence of stratification.

Although vertical diffusivity can be directly determined by observing the spreading of tracers, it is usually inferred from proxies for the turbulent structure of the water column, for instance density inversions (Thorpe, 1977), or small-scale velocity shear. Such observations are typically made in vertical profiles and frequently do not provide either horizontal context or process-level understanding.

Mixing in the ocean is patchy, both in space and in time. The average level of mixing in a given environment therefore represents the cumulative effect of many turbulent events. In interpreting reported measurements of mixing it is important to distinguish between instantaneous measurements, or those representing a single event, from those averaged over some period or spatial range. Values quoted below are averaged values unless stated otherwise, although the nature of the averaging varies.

While a mean vertical diffusivity of around 10^{-4} m^2s^{-1} is required to maintain stratification in the deep ocean (Munk, 1966), it has long been recognised that this diffusion is non-uniformly distributed.

Typical diffusivities from within the water column are at least an order of magnitude lower (10^{-5} m^2s^{-1} or less; (Gregg, 1987; Ledwell et al., 1993)), with compensating mixing hypothesised to take place locally near the bed, at lateral boundaries (continental slopes), and near the surface at high latitudes (subsequently intruding along density surfaces to the ocean interior). Distributions show sensitivity to the nature of bottom topography, with elevated values above complex topography when compared with smooth abyssal plains (Polzin et al., 1997), with a mean value of 10^{-3} m^2s^{-1} above complex topography in the South Atlantic (Ledwell et al., 2000). Global distributions of diffusivity inferred from profiles of velocity shear and density structure (Kunze et al., 2006) show considerable geographic complexity, although they were to some extent predictable using a set of background environmental and forcing parameters. Kunze et al. found a tendency towards elevated mixing in the lower water column, in particular in areas of topographic complexity and high tidal flows, suggesting that interaction between tide and topography is a key mechanism. Values also showed latitudinal dependence. In some areas of low topographic complexity (e.g. the Bay of Bengal), low diffusivities (largely considerably less than 10^{-5} m^2s^{-1}) persisted throughout the entire water column.

Extreme values of vertical diffusivity occur in mixing hotspots, which, by definition, are relatively rare and localised. Diffusivities may be several orders of magnitude higher than typical values. The Atlantis II Fracture Zone provides a conduit for deep water to cross the Southwest Indian Ridge which it does at speeds exceeding 0.25 ms^{-1}. Vertical diffusivities here reach 10^{-2} m^2s^{-1} (MacKinnon et al., 2008), three orders of magnitude higher than typical deep ocean values. A deep water link through the Samoan Passage in the Pacific has revealed comparable diffusivities, with instantaneous values as high as 10^{-1} m^2s^{-1} (Alford et al., 2013). Mixing-driven residual flows in abyssal canyons have shown diffusivities reaching 3×10^{-2} m^2s^{-1} where they interact with sills (St Laurent and Thurnherr, 2007). High diffusivities (10^{-2} m^2s^{-1}) have also been observed deep (2200 m) on the Oregon continental slope where they are tidal in origin, resulting from alongslope tidal flows interacting with topographic roughness (Nash et al., 2007).

4.5 Horizontal diffusivity

Horizontal diffusivity is relatively easily measured near the ocean surface, by observing the spread of tracer patches using remote sensing or rapid in situ techniques. In contrast, it is very difficult to measure in the deep ocean. Large scale dispersion in deep water has been measured by tracer release, but only in the upper water column; in the North Atlantic, at a depth of 310 m, the horizontal diffusivity reached a value of order 1 m^2s^{-1} after 5-10 days after which the tracer was drawn into a set of sinuous streaks (Polzin and Ferrari, 2004). Vertical shear within the bottom boundary layer is estimated to lead to diffusivities of order 0.1 m^2s^{-1} (Richards, 1990). Horizontal dispersion shows strong scale dependency, however. As the extent of a plume increases it will increasingly be stirred by larger scale flows and diffusivity will increase correspondingly.

5. Discussion

5.1 Characterising hydrodynamic regimes

The hydrodynamic nature of the deep sea has been described in terms of a number of processes with differing energy sources, temporal and spatial scales of variability. All of the information required in order to characterise the hydrodynamic nature of any site exists at some level within global datasets. Current fields are available from global circulation models, which continue to improve in their representation of deep flows. Accurate models of barotropic tides and global bathymetric datasets are also available, and empirical distributions of turbulent diffusivity have been described. There are considerable errors, uncertainties and variability in these datasets, however. In particular, observed diffusivities span several orders of magnitude, so confidence in inferred plume behaviour must be low.

An additional problem is the poor resolution of global datasets. Lack of is more problematic than a mere smoothing of spatial variability. Smoothed topography has reduced slope angles, so the tidal criticality of slopes is misrepresented (Zilberman et al., 2009). The size of topographic features compared to the tidal excursion and other flow scales is also misrepresented. Lack of resolution can therefore lead to incorrect assumptions concerning the hydrodynamic nature of a site. Scales smaller than those represented in global datasets are of great importance to processes in the deep sea. In situ observations of currents and detailed local multibeam datasets are, therefore, valuable and likely essential resources for understanding the process level dynamics of a given site. Ideally, observations would include time series capable of identifying extreme events (e.g. benthic storms), as well as relatively high-frequency phenomena (e.g. bores). High-resolution profiles of density and velocity structure, extending as close to the bed as is practical, would supplement these datasets and enable vertical diffusivities to be estimated using either density inversions (Thorpe, 1977) or shear-based methods (D'Asaro, 1982).

5.2 Implications for the differing discharge methodologies

As described previously, three discharge methodologies are under consideration here (Table 1). These will be considered individually from a hydrodynamic perspective.

A) Dissolution and resuspension of tailings deposited on the seabed.

The key consideration for the resuspension of previously settled tailings is of the likelihood of extreme current events. In this context, ‘extreme’ is taken to mean extreme for the site in question, since ongoing deposition of material can be assumed to occur under ‘typical’ conditions. Resuspension of accumulated material requires an atypical period of elevated bed stress. Material will always be initially suspended into the bottom mixed layer. Although the mixed layer is likely to be of increased thickness during such events, escape into the adjoining stratified water column is dependent on processes that lead to flow separation, such as fronts, bores or lee effects behind a topographic feature, or mixing against a slope. The occurrence of resuspension at times of strong currents and a thick mixed layer, means that there is considerable potential for the resuspended material to travel large distances before it settles.

An additional consideration is that sites that are prone to extreme (high current) events are also, in their natural state, subject to frequent re-working of bed material, including erosional events, depositional events, and long-distance transport of material. Such sedimentary effects have been widely reported in the literature (Hollister and McCave, 1984; McCave, 2009). Settling and resuspension events are therefore the norm in these environments, and resident fauna may be expected to be tolerant to them.

B) Pumped, and potentially buoyant, discharge of dissolved and suspended materials from a pipe sited at depth

Of the three discharge methodologies under consideration, this category will exhibit the greatest variation in nature. Initial (i.e. at point of release) discharge characteristics can vary in buoyancy, momentum, and particle size distribution. Furthermore the depth (or height above the bed) and orientation of discharge can vary. All of these factors (buoyancy, momentum, orientation, height above bed and particle size distribution) will influence the way in which the discharge flow interacts with ambient flows. The most general statement that can be made about this discharge methodology, when compared with either A) or C), is that there will be a greater likelihood of discharged material escaping from the bottom boundary layer, or indeed being delivered directly above the boundary layer. Under this scenario vertical diffusion of the discharged material may be reduced, whilst horizontal dispersion may be enhanced. Initial dilution will to a greater extent depend on buoyancy and momentum of the discharge. However the interaction between a forced buoyancy plume and one of the regular (tidal) or irregular (e.g. Benthic storms) turbulent processes outlined above could significantly alter the undisturbed plume discharge dynamics. The alteration would always be to increase rather than decrease initial dilution. Typically, discharge momentum and buoyancy will become vanishingly small within tens to hundreds of metres of the discharge point, noting that discharge momentum will typically become negligibly small over a shorter distance than the buoyancy, and that buoyancy acts only in the vertical direction.

C) Direct mechanical disturbance of the seabed.

While direct mechanical disturbance of the bed superficially resembles discharge method (A) in its location at the sea floor, it differs in the nature of the material suspended (reflecting the ambient composition of the bed) and in the conditions under which it occurs (not limited to energetic events). Such suspension may occur in low energy conditions, when the bottom mixed layer may be small. The discussion above concerning mechanisms for exiting the mixed layer applies equally here, although there is an additional possibility that turbulence generated by the seabed machinery (or flows past this machinery) will also play a role in initially mixing suspended material, and even stirring it out of the mixed layer. The further material is able to rise above the bed the greater the potential is for significant lateral transport before it settles.

5.3 Can we predict atypical or extreme environments?

Atypical sites are identified here as those with high energy levels, which also tend to have elevated levels of turbulence and diffusivity. These sites are, by definition, rare and/or localised. Deep sea sites that have been identified as having extreme energy levels include:

- Deep water connections: Where a narrow gap provides an important conduit for deep water to pass between ocean basins, elevated current speeds lead to enhanced mixing, and a plume would be expected to become widely dispersed.
- Tidally critical and supercritical slopes in regions with a significant cross-slope tidal component:
- Areas beneath energetic and variable surface currents may experience variability induced by eddies and meanders in the overlying water column, leading to occasional extreme events (benthic storms), and substantial resuspension and redistribution of settled material.

These sites are all relatively easily identified, especially if in-situ current records are available.

5.4 Will there be surprises in store?

In assessing a given site, even using a detailed and accurate local hydrodynamic model, there will always be some uncertainty in predictions of expected dynamics and mixing levels. In large part this uncertainty arises from the unknown effect of remote processes. These may include beams of internal tidal energy from a distant source, or propagating remotely-generated eddies.

6. Summary

The hydrodynamic nature of deep sea sites shows considerable variation according to local conditions, including the nature of the topography, geographic latitude, tidal behaviour, relation to surface currents and the large scale ocean circulations. The initial behaviour and dilution of a mining discharge will depend on flows at scales of hundreds of metres or less, encompassing turbulent processes down to viscous scales (centimetres and below).

Deep sea dynamics on these scales are both complex and poorly understood, although considerable steps have been made in recent years, driven in part by the importance of deep sea mixing to the oceanic meridional overturning circulation, a key component of the climate system. In this report, the hydrodynamic processes of the deep sea are reviewed with particular focus on those that have significant implications for mining discharges. These include processes that lead to enhanced current speeds or turbulence in the lower water column, and those which lead to flow separation from the benthic boundary layer, providing a route for suspended material to enter the adjoining stratified water column.

The potential for characterising potential mining sites using existing global datasets or detailed site-specific observations is considered. While appropriate datasets exist, the potential for misrepresenting hydrodynamic processes is highlighted. This does not result merely from the low resolution and smoothing inherent in global datasets, but from a fundamental need to resolve small scales to understand deep sea physics. It is recommended that detailed multibeam bathymetry and in situ current time series combined with repeated density profiles provide a sounder basis for identification of the hydrodynamic processes that characterise a given site.

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