

PLUMES FROM DEEP-SEA MINING

Mining of the seabed will create plumes of fine particles, which will travel across the seabed away from the mined area. In addition, the ore slurry transported to a ship at the sea surface will need to be dewatered and the waste water returned to the sea, creating a discharge plume. The behaviour and impact of these plumes depends both on the nature of the material they contain and of the currents that transport, mix and disperse them. While currents in the deep sea are usually slower than those near the surface, they can be highly unpredictable and turbulent. As a result, plume behaviour may differ markedly between sites, even when these sites lie close to one another. The location of the most turbulent sites can be predicted to some extent, but the inherent complexity of the processes involved and their intermittency means that a range of plume behaviours should be anticipated in assessing potential impacts.

Deep-sea currents are different to surface waters

Currents and flow patterns at depth in the ocean differ markedly from those near the surface in several important respects. The movement of water in the ocean is largely driven by surface influences, including the direct action of wind, as well as indirect effects that modify the density of water near the surface, such as evaporation, rainfall or solar heating. The result is that deep flows are typically considerably slower than those near the surface. However, they are also frequently more complex, three-dimensional and turbulent because density stratification, which tends to suppress turbulence, is more pronounced near the surface. These complexities, combined with the technological challenge of measuring currents several kilometres beneath the surface of the ocean, mean that the flow environment that will be encountered by deep-sea plumes is imperfectly understood.

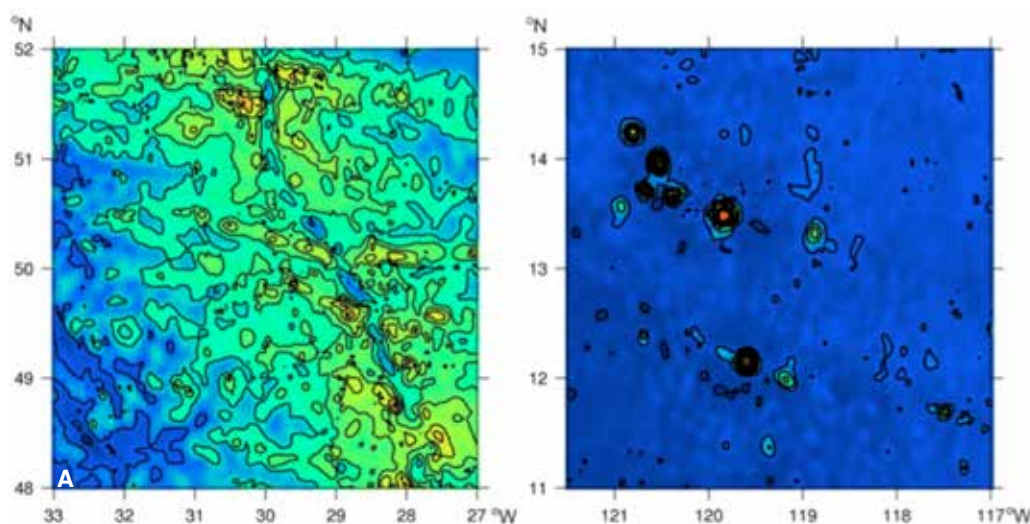
The nature of a plume

A plume resulting from mining activity will contain a mixture of dissolved material and suspended particles of a range of sizes. Dissolved material is transported inextricably by the water that contains it, whereas suspended particles have a tendency to sink. Large particles sink faster than small particles, so they rain out of a plume and settle on the seabed near its source; finer particles and dissolved material are transported

greater distances. Seabed accumulations of plume material will therefore be thicker and contain larger particles close to the source of the plume. A more turbulent environment delays the settling of particles on the seabed by stirring them higher into the water column. This spreads the impact of the plume over a wider area while also reducing its intensity. Whether this is considered a greater or a lesser impact depends on the tolerances of the particular environment considered. Near-bed currents may also erode and redistribute material that has previously settled on the seafloor; some locations experience intense 'benthic storms' as surface eddies pass, and these events can dramatically rework seafloor sediments.

Differing deep-sea topographies

The main driver of complexity in deep-sea flows is the interaction between large scale currents, tides and the topography of the seabed. Deep-sea topography is hugely varied but two broad classes, that together account for much of the deep ocean, are the relatively flat abyssal plains, and the steeper, more complex mid-ocean ridges. Both types of environment are of interest from the perspective of mineral extraction. While abyssal plain sites are largely of lower complexity, they are scattered with isolated hills or seamounts of varying size and steepness, which do have implications for plume behaviour.



Contrasting deep-sea topographies: A) the Mid-Atlantic Ridge and B) the Clarion-Clipperton Zone of the Pacific. These figures are based on satellite derived data (Smith and Sandwell, 1997). The contour interval (black lines) is 500 m and each extract covers around 440 km x 440 km.

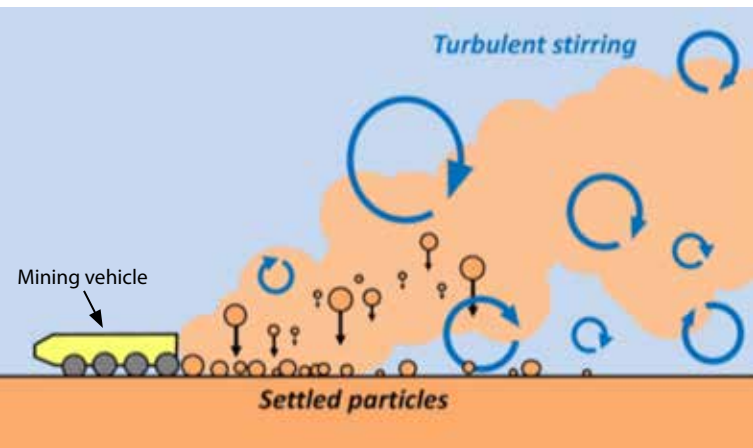
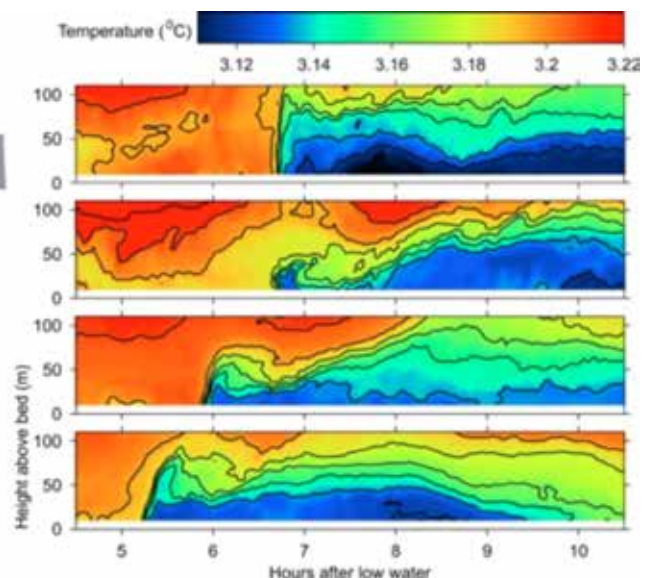
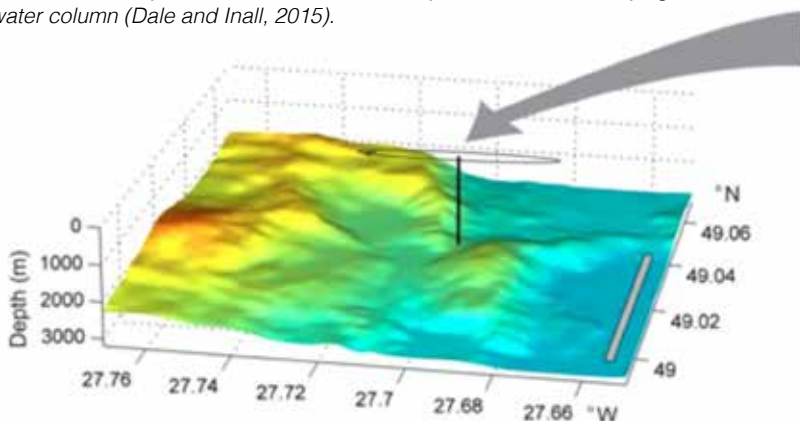


Figure 2: A sediment plume in the deep sea. Settling particles of a range of sizes are shown. In this case, plume material has separated from the bottom boundary layer and entered the overlying water column.

Waves, tides, fronts and bores

From the perspective of understanding the nature of plumes and their impact, the key flow processes are those that mix the plume-containing water, stir it horizontally, or separate it from the seabed such that plume material can be found outside the bottom boundary layer in the water column. It is known that mixing tends to be most intense above complex topography, but the processes responsible are incompletely understood. When the stratified density structure of the ocean is pushed up or down a sloping seabed this generates 'internal' waves within the water column, which can transport energy away from the

Figure 3: Turbulent bores of cool water amid complex mid-Atlantic Ridge topography. These features are tidal-generated, but variable and intermittent. They lift and stir bottom boundary water into the overlying water column (Dale and Inall, 2015).



Further reading

Dale, A.C., and Inall, M.E. (2015) Tidal mixing processes amid small-scale, deep-ocean topography. *Geophysical Research Letters* 42, 484-491.

Garrett, C. and St Laurent, L. (2002) Aspects of deep ocean mixing. *Journal of Oceanography* 58 (1), 11-24.

Richards, K.J. (1990) Physical processes in the benthic boundary layer. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences* 331 (1616), 3-13.

seabed and may locally 'break', leading to isolated patches of intense mixing. Tidal currents against a slope generate internal waves which may also be highly turbulent against the seabed when the gradient of the slope falls within a critical range. Tidal sloshing of water up and down a slope may steepen into sharp density jumps, or bores, which travel along the seabed and effectively peel water away from the bottom. This would allow plume material to enter the overlying water column. Similar processes also occur as tides pulse dense water over ridges or bumps (Figure 3). Even steady flow over obstacles may generate lee waves and intense downstream turbulent patches when the speed of flow and the scale of the bump are appropriate. In abyssal plain topographies, therefore, intense turbulent mixing may occur in flat areas downstream of a topographic feature, and even relatively small seabed bumps (hundreds of metres across) are expected to lead to this sort of behaviour. Extraction operations may therefore encounter intensely turbulent patches which strongly influence the nature of the plumes generated.

Predictability

While there are combinations of flow speed, bottom steepness, topographic scale and complexity that are conducive to producing the most turbulent environments, these phenomena are very difficult to predict with certainty, even in situations where there is excellent understanding of local topography and currents. Turbulent processes are patchy in space and intermittent in time, so predictions of the net impact of plumes must therefore consider a range of scenarios.