Seabed Mineral Deposits: An Overview of Sampling Techniques and Future Developments

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A B S T R A C T

The accuracy, precision and representativeness of seabed sampling are critical to the reliable estimation and exploitation of seabed resources. As well as overcoming the challenges faced by conventional land-based sampling techniques, seabed sampling methods must surmount issues arising from the remote sampling of targets conducted from a base of operations (a vessel) that is constantly in motion due to the dynamic forces of wind, waves and ocean currents.

An overview of established seabed sampling techniques is presented, with a discussion of their respective benefits and disadvantages, as determined from their application in sampling of seabed resources currently under development around the world. Quality of sampling is a critical ingredient in the confident estimation of mineral resources and is a key criterion to be assessed when reporting resources in accordance with an internationally accepted reporting code (e.g. the Australasian Joint Ore Reserves Committee (JORC) Code or the Canadian Institute of Mining, Metallurgy and Petroleum (CIM) National Instrument 43-101 (NI 43-101)).

This paper highlights the challenges of representatively sampling the seabed and how they can best be overcome, within the limitations imposed by various marine exploration environments.

Keywords:
seabed sampling
seabed resources
dredge sampling
grab sampling
box core
gravity core
piston core
vibrocore
surface drilling
seabed drilling
representative sampling

9 February 2015

INTRODUCTION

Seabed exploration and mining is at the forefront of development within the minerals sector. The first deep-sea mineral resource that was reported in accordance with an internationally accepted reporting code was defined in 2008[1] and since then four further seabed resources have been reported under such codes[2]. Several other seabed resources are under development and there are calls to standardise resource reporting within the marine minerals sector[2,3]. This will enable those responsible for estimating a resource to better scrutinise poor sampling practices, and will lead to better clarification of confidence in the mineral resources, and ultimately to more successful mining plans[2]. Furthermore, it will promote new technologies for reliable sampling techniques.

Seabed exploration is a logistically challenging undertaking and, in contrast to land-based exploration, physical sampling is generally significantly more expensive than conducting remote sensing surveys. While reconnaissance

Cite. Ref.: Sterk, R. & Stein, J.K. (2015) Seabed Mineral Deposits: An Overview of Sampling Techniques and Future Developments. Paper presented to: Deep Sea Mining Summit. Aberdeen, Scotland. 9-10 February 2015. 29 pp.

survey methods such as acoustic backscatter are widely used to identify and delineate surficial seabed deposits (namely nodule deposits)[4-6], physical sampling is necessary, to ground-truth any type of remote-sensing data, and to obtain the most accurate value of the concentration of a mineral commodity for a given volume or mass of material.

Accuracy, Precision and Representativeness

There are three fundamental principles with regards to sampling which, unless properly addressed, will result in unreliable sampling data and could result in project failure. The cost and financial impact of bad sampling has been well documented and discussed in the land-based mineral exploration setting[7,8]. All aspects of the sampling equipment or method, sample spacing, size, frequency, etc. can be included in these (simplified) definitions:

> *Accuracy* – A measurement is accurate if it, or the average of a number of measurements is close to, the real value. A measurement that is accurate is one that is free of bias.
>
> *Precision* – Precise measurements have a dispersion about their mean value which is lower than a specified dispersion. The level of dispersion is defined with the purpose of separating measurements that are entirely fit for a particular purpose and those that are not. Essentially, it is a measure of sample reproducibility and is related to ore characteristics.
>
> Precision is commonly expressed as the variance between data points or datasets. This variance includes a 'natural intrinsic variance' that depends on the type of ore that proper sampling cannot adequately capture, as well as a variance that is due to poor sampling and sampling errors.
>
> *Representativeness* – This determines whether a sample or group of samples is suitably representative for the population (e.g. representative of location, grade distribution, constituents, etc.). A sample is said to be representative if it is unbiased (i.e. any fragment in the material to be sampled has the same, unrelated probability of being collected) and has a sufficiently small variance (i.e. is sufficiently reproducible).

For instance, a bucket-grab sampler that spills fine material as a sample is brought up to a vessel, will bias the sample and result in an *inaccurate* measurement of grain size, mineral concentration, etc. A small-diameter core sampler will retrieve a smaller volume of material compared to a large bucket-grab or box core sampler collecting from the same area and therefore will show less *precise* data. Deposits with a high degree of inherent variance (i.e. have a high 'nugget effect') are commonly associated with poor *precision* in sampling (i.e. the difficulty in obtaining the same results when sampling the exact same area more than once). When collecting several dozen samples using an ROV in a high-grade area by 'grabbing' samples from sea mounts, these samples are not *representative* for the larger ore body as they do not test the grade of the material within the mount or below it. They will also show poor *precision*.

International Reporting Codes

Code-compliant reporting of mineral resources and reserves is a concept that is well defined, widely accepted and fully implemented within the commercial land-based exploration and mining sector (see Sterk and Stein (2015)[2] for a discussion). To avoid confusion, in this paper the term '*mineral resource'* means a resource 'reported in accordance with an internationally accepted reporting code (i.e. such as JORC or NI 43-101) and estimated (or based on documentation prepared) by a qualified/Competent Person as defined by such a code'.

SEABED SAMPLING METHODS

Numerous challenges are encountered by traditional explorers and miners attempting to collect accurate, precise and representative samples (hereafter collectively referred to as 'reliable samples') of terrestrial deposits. Deep-sea explorers face even greater hurdles on top of conventional sampling difficulties, not least because they are attempting to conduct sampling from a base of operations that is constantly in motion and often remote (<1 – 5 km) from the point of sample collection whose location is inherently imprecise.

Several methods of sampling the seabed have been developed over recent decades, from comparatively crude methods such as dredging, through to the latest innovative technology involving highly skilled operators remotely controlling robotic drill rigs deployed on the seabed. While higher-tech sampling systems may be able to provide better quality samples (depending on sampling objectives), they can prove significantly more expensive than traditional systems, and being more complex they require extensive management and maintenance to prevent costly and time-consuming breakdowns.

Obviously it is desirable to gather the most reliable sample data from the outset of a project, by utilising the most appropriate sampling equipment for the deposit. However, most projects, especially those in the early stages of exploration, are bound by significant financial constraints; risk, confidence and expenditure are precariously balanced, and operators need to make a conscious compromise between sample quality, sample quantity, and budget. This paper provides a general overview of the sampling methods currently being employed by seabed explorers, which will help operators choose suitable techniques to establish high-quality sample data from which they can reliably estimate a resource. The pros and cons of the various systems are discussed, including sampling objectives and/or operational environments to which they are best suited, as well as some of the difficulties which can be encountered when employing each method.

Seabed sampling systems (Figure 1) can be divided into three general categories: those that are towed along the seabed (e.g. dredges), those that spot sample the surface of the seabed (e.g. opposing-jaw bucket-grabs and box core samplers), and those that are capable of penetrating up to many metres into the seabed and (generally) produce cylindrical cores (numerous corers). The latter category can be further divided into simpler coring systems that can be deployed from most vessels equipped with a winch and wire cable (gravity corers, piston corers and vibrocorers) and much more complex drilling systems that require specialised or specially equipped vessels to be deployed (vessel-mounted and seabed drilling systems).

Each system has its own particular strengths and weaknesses. Commonly utilised methods are discussed loosely in order of increasing equipment complexity, followed by a discussion of some problems that can be encountered when using the sampling systems.

Towed Sampling Tools

Dredges

Arguably the crudest form of seabed sampling, dredging involves deploying a simple collector from a vessel and towing it along the seabed to collect surficial sediment. Most dredges in use today consist of rigid and enclosed boxes[9] or large chain-bags with a reinforced (e.g. steel frame) opening[5,10,11] (see Figure 1b). Historically, pipe-dredges, composed of simple steel pipe enclosed at one end, have also been used[12]. Dredges are mostly used for sampling

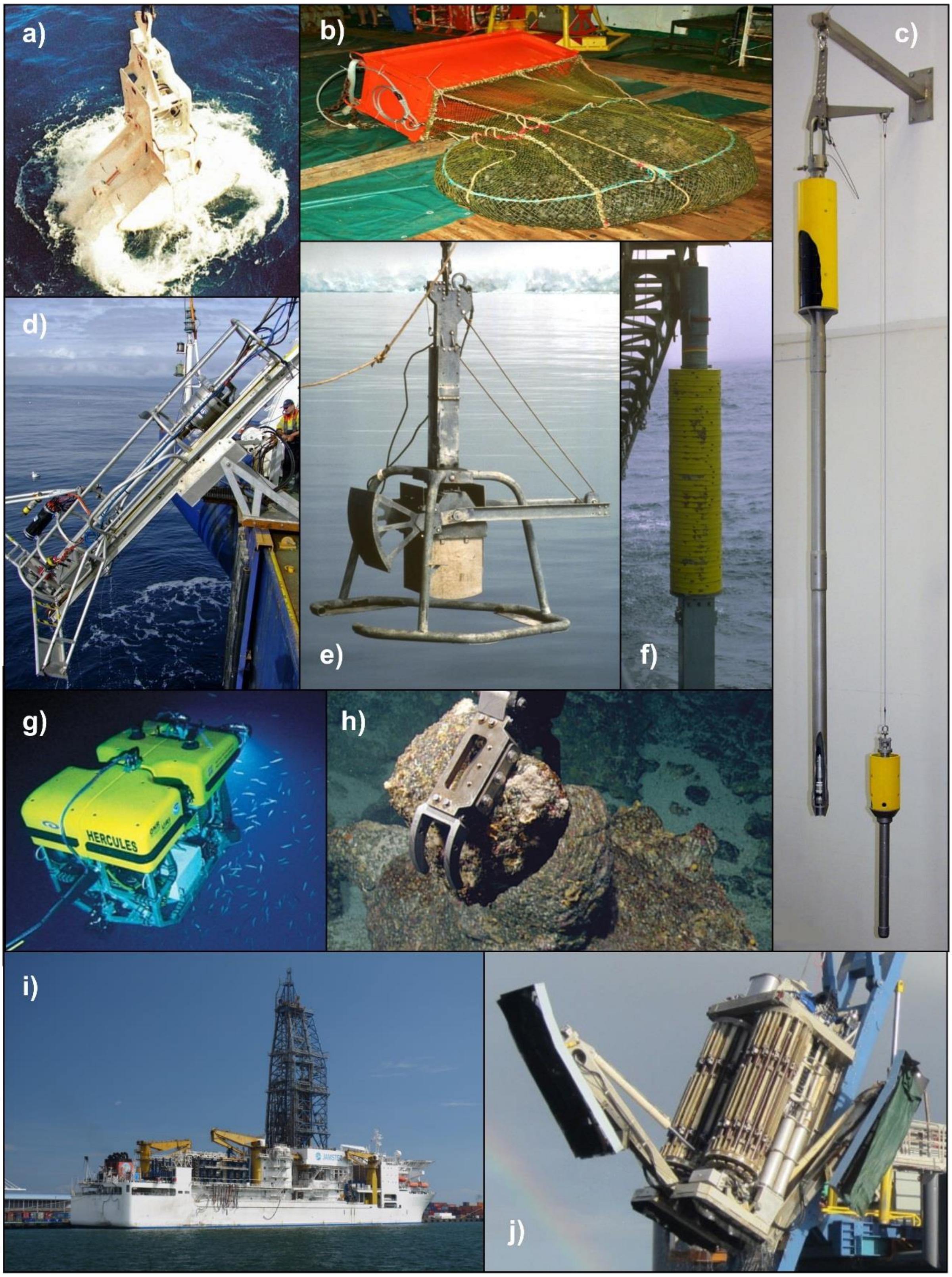

Figure 1: Seabed sampling equipment: a) large pneumatic bucket-grab sampler, b) chain bag dredge, c) conventional piston corer, d) vibrocorer, e) box core sampler, f) gravity corer, g) ROV and h) ROV grab sample, i) drilling vessel for vessel-mounted (surface) drilling, and j) seabed drill. (Images courtesy of: a) von Rad (1984), b) IOM, c) Hannes Grobe , d) CRP, e) Hannes Grobe, f) Hannes Grobe, g) & h) Ocean Exploration Trust, University of Rhode Island, i) (open source), and j) Benthic).

seabed nodules (polymetallic or phosphorite)[5,10,12], but their use has also been reported during exploration for seafloor massive sulphides (SMS)[13] and ferromanganese crusts[14].

Dredges are cheap and relatively easy to deploy. The open mesh of chain-bag dredges enables fines to be washed out during sample collection, meaning they are useful for presence/absence reconnaissance surveys and for collecting bulk samples of seabed nodules, but are not capable of collecting representative samples of bulk sediment due to the loss of fines. Box dredges enable better preservation of fines, but still suffer from losses associated with the uppermost 'liquid' sediment layer and washing of the sample during dredge retrieval. The lack of control over sample collection means the seafloor location of the dredge samples is very imprecise (dredges seldom have transponders for echo location). Similarly, dredges have poor penetration capability, particularly if the seafloor is hard or if nodule size and spacing are such that the mouth of the dredge cannot penetrate a nodular 'pavement'. Recovery of nodules will be poor if they are buried in the sediment. Depending on their mouth size, dredges also have the potential to further bias sampling by excluding larger nodules and rock fragments. For these reasons, sampling data from dredges should not be used in the estimation of mineral resources.

Spot Sampling Tools

Bucket-Grab Samplers

While 'grab samples' is a term used by seabed explorers to refer to samples collected with a large bucket-style sampler (an 'equipment' term), it is also a term used universally in the wider mining industry to refer to any samples collected by simply 'grabbing' a piece of rock with various kinds of equipment (a 'method' term). The latter 'grab samples' are notoriously unreliable, primarily because they do not give every part of an outcrop within the sampling area the same chance of being collected. Consequently, 'grab samples' in a conventional mining sense exhibit high bias, poor precision and are never representative[7]. To avoid confusion and negative connotations with this highly inconsistent *method* of sampling, in this paper we refer to the seabed equipment as 'bucket-grab samplers' to make it clear that this refers to samples collected using conventional marine sampling *equipment* that has a consistent method of operation and sample retrieval.

A variety of bucket-grab-style samplers are commercially available 'off the shelf', while others have been developed as prototypes by pioneer seabed explorers. Bucket-grab samplers (see Figure 1a) come in a variety of different types and sizes, and have several different closing mechanisms. In general they all consist of a pair of opposing jaws that are locked in the open position upon deployment and are lowered or allowed to free fall to the seafloor, at which point the lock is released and the bucket-grab's jaws close. Bucket-grabs either close under their own weight as the apparatus is raised from the seabed (simple mechanical closure; e.g. clamshell-style), assisted by the movement of arms drawn upward by the wire cable (e.g. van Veen-style) or with additional closing power (e.g. pneumatic closure)[12]. Bucket-grabs with assisted closure (or extremely heavy versions) tend to experience fewer sampling failures by breaking large nodules or rock fragments which may jam in the jaws and would otherwise prevent full closure, allowing the sample to be washed out[12]. They can therefore collect samples that are generally more accurate than lightweight bucket-grabs with unassisted closure. Bucket-grabs with powered closure also tend to be larger, resulting in larger volume samples that are therefore more precise.

The main problem with bucket-grab samplers is that due to their geometry and mechanism of closure, they do not sample all sediment within the open area of their jaws down to the same penetration depth. That is, the curved trajectory of the closing jaws recovers more of the upper sediment than the lowermost sediments. Bucket-grab samplers therefore do not always constitute a representative sampling method and will introduce a bias if not carefully managed. This lack of representativeness means that, in the case of seabed nodule deposits, bucket-grab samplers will often underestimate the nodule abundance at a sample site by leaving some buried nodules behind[12,15]. The only exceptions to this may be deposits where the nodules are concentrated at the surface (e.g., manganese nodules) and where the jaws encounter a resistant surface long before reaching their maximum penetration depth and scrape along the surface (such as a stiff clay horizon) as they close. In such cases a bucket-grab may be able to collect all of the overlying unconsolidated sediment within the area of its jaws, as long as the sediment volume does not exceed the capacity of the grab bucket[12].

Bucket-grab samplers can either be deployed as buoyant ‘free fall’ apparatuses that release weight at the same time the closing mechanism is engaged, and which have floats to return them to the surface[11,15], or as wire-retrievable bucket-grabs that can be lowered to an approximate distance above the seabed and allowed to free fall the remaining distance (by allowing the winch to run out freely)[12].

A number of issues can be encountered with bucket-grab samplers. As they approach the seafloor they can generate a bow wave that can wash sediment (and nodules) out of the area to be sampled[12]. This would bias the sample and make it less accurate. This can be minimised by having large vents or openings in the bucket-grab jaws to allow water to pass through them during descent. To prevent washing of the sample during ascent as well as exposure to washing by surface waves these vents must be closed upon retrieval of the bucket-grab if a representative bulk sediment sample is to be obtained [12]. Some sampling campaigns choose not to collect representative bulk sediment samples and instead focus on collecting nodules only (solely for the purposes of determining nodule abundance, kg/m^2). Such campaigns may use bucket-grab samplers that are not completely enclosed when the jaws are shut[11], allowing fines to wash out upon retrieval. This sampling method will result in non-representative samples that do not have the reliability of bulk sediment samples.

If bucket-grab samplers are to be used for estimation of a mineral resource, then the sampling process needs to be carefully controlled through appropriate Standard Operating Procedures (SOPs). Whether they are used to obtain concentration data or ‘abundance’ data, care must be taken to minimise bias. Large bucket-grab samplers are often well-suited for nodule sampling as they provide a suitably large sample, which will lead to better precision if well managed. In the case of a nodule deposit, they are only representative if the entire layer is cut consistently.

Box Core Samplers

Box core samplers (see Figure 1e) consist of a simple square (or rectangular) box, typically with several tens or hundreds of kilograms of weight attached to the top. The box core sampler is lowered to the seabed on a wire cable. On contact with the seafloor a release mechanism is triggered that enables the box to penetrate the sediment under its own weight. Recall of the wire first pulls a hinged arm upward causing an attached plate (‘shovel’) to slide into place across the base of the box, enclosing the sampled sediment, before the sampler is retrieved from the seabed[12]. Box core samplers can have single or dual-closing shovels which, similar to bucket-grab samplers, can be prevented from properly closing by large nodules or rock fragments becoming wedged in the closing mechanism[12]. Box core samplers must also be vented to prevent bow wave development upon descent that can wash sediment out of the sampling area immediately prior to impact with the seafloor[16]. While box core samplers are useful tools in soft or moderately cohesive sediment, their generally small dimensions (≤0.5 m^2 sampling area) means sample volumes may not be large enough to provide precise measurements in coarse-grained and/or deposits with a high intrinsic grade variability. They also generally have poor penetration ability in coarse grained, indurated, or hard rock substrates, often making them non-representative and generally ineffective at sampling deposits such as coarse grained and/or closely packed nodule deposits and ferromanganese crusts[16]. Similarly their shallow penetration capability makes box core samplers undesirable for reliably sampling consolidated polymetallic sulphide deposits, which tend to be several metres thick[16,17].

Box core samplers have an advantage over bucket-grab samplers in that their square (or rectangular) geometry means they sample all of the sediment within the sampling area of the 'box' down to the same penetration depth (assuming the box corer penetrates the seabed at right angles to the sediment-water interface and is not inhibited by any obstacles such as a large nodule or rock fragment). This makes them more representative than bucket-grab samplers if managed well and when used to sample appropriate sediment types. In addition, their general availability and ease and efficiency of use has seen box core samplers become a standard sampling tool alongside bucket-grab samplers, utilised by numerous seabed explorers working on sedimentary seabed deposits (nodules and sedimentary SMS). They are currently the tool of choice for most explorers seeking to ground-truth nodule abundance interpretations made from remote sensing data (such as acoustic back scatter imagery)[5,11,18-21].

Some long square cross-sectional area samplers referred to as 'box corers' by some explorers have a much longer/taller 'box', up to several metres in length, that is driven into the sediment under significant weight (up to and in excess of 4 tonnes) (e.g. a heavy kastenlot)[17]. These do not have closing shovels to retain the sample, however, most versions have some form of core catcher such as internal flaps that close upon retrieval to prevent the sample from washing out [22,23]. In operation, and in terms of penetration depth, they are very similar to conventional circular cross-section gravity corers (discussed below). Their advantage over conventional gravity corers is that they tend to have thinner barrel walls, which assist penetration, and also can have better sample recovery than gravity cores collected with equivalent penetration depths in comparable sediment[23].

In theory, box core samplers provide a more reliable sample than the bucket-grab samplers. However, many practical issues need to be very carefully controlled and documented for each sample following a detailed SOP. Competent Persons aiming to include data from box core samplers in a mineral resource estimate need to assess each data point carefully and reject those data which are not of good enough quality.

ROV Grab Samples

Remotely Operated Vehicles (ROVs) are a fundamental multi-function tool in the seabed exploration inventory. They are widely used within the offshore oil and gas industry, as well as for research and solid mineral exploration purposes. Different systems are equipped with a range of functions; however, the general configuration is that of an un-manned, self-propelled unit controlled via a tether or load-carrying umbilical to an operator aboard a surface vessel. Simpler systems may only be equipped with a camera and lights, while more sophisticated systems can be equipped to carry out precise underwater maintenance, testing or sampling tasks. They generally are 'free-flying', however some systems run on tracks or wheels along the seabed. Tether Management

Systems (TMSs) enable ROVs to be utilised even in strong currents, and high-pressure rated systems are capable of operating at depths in excess of 8,000 m[24,25].

Video and still images of the seafloor, captured and transmitted in real time to an operator on board a vessel, can be used to monitor the progress of other sampling equipment or to generate photographic profiles of the seabed. This is particularly useful for reconnaissance surveys and first order analysis of nodule abundance for polymetallic and phosphorite nodule deposits. More complex systems with one or more hydraulically operated arms can be used to take ‘spot’ or ‘grab’ samples of the seabed (see Figure 1g-h). Samples collected during ROV operations can be stored in numerous compartment boxes secured under the ROV (up to 15 kg) or a basket lowered on a separate wire independent of the ROV for larger samples[26,27].

Grab samples (here referring to the method of sampling rather than conventional seabed sampling bucket-grab equipment; see discussion under Bucket-Grab Samplers above) are notoriously unreliable because they generally only recover surface material. Seabed solid mineral deposits actively form, all or in part, by precipitation from their surroundings, whether seawater, sediment pore water or hydrothermal fluids[28-30]. Consequently marine solid mineral deposits tend to exhibit zoning to some degree (both locally and at the deposit scale), due to the changes in water/fluid composition over the several decades to millions of years required for their accumulation (depending on the type of deposit). ROV grab samplers do not penetrate the full profile of mineralisation at any one sample location and consequently there is always some material that has a zero chance of being collected, creating a large bias and precluding samples from being representative. This type of sampling is also often only carried out in high-grade areas, introducing further bias into sample data. These significant biases mean grab samples are not representative samples and extreme caution should be exercised when these data are used in mineral resource estimations.

In the case of nodule deposits, grab sampling cannot be used to determine nodule abundance, nor will it collect representative samples for geochemical analysis as the geochemistry of both phosphorite[31] and manganese[32] nodules varies depending on nodule type and/or nodule size.

ROV grab sampling could ostensibly be used to sample polymetallic crust deposits due to their generally thin (<25 cm) and surficial mineralisation. Large grab samples have the potential to penetrate the full thickness of mineralisation in these cases, however the poorly constrained sample sizes associated with randomly breaking off pieces of rock mean grab samples will always be imprecise and not necessarily comparable to one another. For the purpose of resource definition (rather than reconnaissance) sampling, sample collection should be carefully planned (i.e. grid-based sampling) so that higher and lower grade areas are equally sampled.

ROV grab samples have been used to sample polymetallic sulphide deposits, specifically ‘chimneys’ of sulphide formed from sulphide precipitation immediately around hydrothermal vents exuding from the seabed[27]. The narrow, vertical geometry and solid nature of these structures has hitherto precluded them from being sampled by any other means. They are too hard to be sampled by non-drilling enabled sampling systems, and established drilling techniques are not practical because they are optimised for vertical coring and have limited landing capability on exposed chimney mounds. Consequently, chimneys have been collected using an ROV’s hydraulic arm to break a piece off a chimney which, once recovered, is sliced or cut radially through the full width of the chimney fragment to obtain a sample for geochemical analysis. Tooling such as chainsaws and disc cutters are readily available for Work Class ROVs, which enable large samples to be taken that are more representative of the chimney mineralogy as a whole. Obviously this sampling technique is not ideal as it only samples the uppermost part of a chimney and collects no material from the chimney base (or subsurface), and so does, in effect, only retrieve a surface sample. Consequently ROV grab sampling is unable to representatively sample the full mineralised profile.

Despite these drawbacks ROV grab sampling has been used to estimate a chimney resource[27]. In this case good correlation in the grade of chimney grab samples and adjacent duplicate samples showed sample precision was sufficient to be able to estimate a resource to the inferred level of confidence. Depth of chimney mounds was interpreted based on an automated algorithm considered to be geologically reasonable. However, in the opinion of the Competent Person, until the chimney mounds are tested by drilling, their grade, density and depth should be considered of low confidence[1,27].

Similar to other sampling methods, precision of grab sampling for any programme should be investigated by collecting duplicate samples. Even though this may show acceptable results, it is discouraged to include these types of samples in mineral resource estimations as they are not representative and will often lead to significant positive bias.

Non-Automated Core Sampling Tools (drop corers)

Gravity Corers

Gravity corers (see Figure 1f) are the simplest form of coring device and consist of a pipe or barrel, typically with several tens to hundreds of kilograms of weight added to the top. The gravity corer is lowered close to the seafloor on a wire cable and then allowed to free fall into the sediment (by allowing the winch to run out freely). Depth from seafloor at which the wire is released can be estimated from the amount of wire out, or more accurately by using an acoustic beacon. The gravity core barrel can vary in length and diameter depending on a programme's particular sampling objectives. The core barrel is usually lined with a plastic core liner, enabling the cored sediment to be more easily extracted upon retrieval. Most systems also employ some form of core catcher to prevent a sample washing out upon retrieval.

The amount of additional weight can be varied and directly affects the penetration power of the corer. A check valve can be installed in the top of the barrel to allow water to flow out of the barrel during penetration of the seabed and enables sediment to enter the barrel and liner unimpeded. The closed valve during ascent prevents the loss of the cored section by preventing water from washing the core out of the barrel[33].

Gravity corers are capable of penetrating many metres into sedimentary seabed. However, the corer's long length but small diameter (both cylindrical and non-cylindrical, square cross-section variants) means only a small amount of each successive sedimentary horizon is sampled compared to the overall volume of an entire core. The small core diameter results in less precise sampling data and they are therefore not practical sampling tools for deposits with a large average nodule size or with a large intrinsic grade variability. While gravity corers are useful for sampling soft, cohesive sediments, even with some form of core catcher, non-cohesive sediments can wash out of the sampler during retrieval, leading to a biased and inaccurate sample. Conversely, hard rock horizons (or a large boulder within otherwise soft sediment) can prevent penetration of the gravity corer into the seabed, leading to problems with representativeness, and poorly constrained depth of mineralisation. Depending on the dimensions and weight of the corer, encountering such obstacles can also damage the equipment, most readily by causing a bend in the core barrel.

The small cross-sectional area of gravity corers and lack of penetration power in hard substrates precludes gravity corers from being used to effectively sample coarse grained- and hard crust-type seabed deposits. They can be effective at sampling fine grained sedimentary deposits and have been used to carry out resource definition sampling of fine grained phosphorite sands off the coast of Namibia[34], as well as fine grained sedimentary SMS in the Red Sea[17].

Data from gravity corers need to be assessed in detail before they can be used in mineral resource estimations. If suitable to the deposit type and if controlled by robust SOPs they can provide reliable data for such estimations.

<u>Conventional Piston Corers</u>

Conventional piston corers (see Figure 1c) are similar to gravity corers in that they consist of a lined pipe or barrel, of variable length and diameter, which is deployed using a winch and wire and allowed to penetrate the seabed under its own weight (although additional weights are typically added to improve penetration power). In contrast to gravity corers, conventional piston corers have a piston set at the bottom entrance to the barrel that moves up the barrel as it penetrates the seabed, helping to draw core into the barrel more effectively. A conventional piston corer is deployed on a wire cable with a pilot weight (sometimes a small gravity corer) attached to a secondary cable connected to the arm of a quick-release mechanism attached to the top of the primary coring barrel and the primary wire cable. The primary cable is held with a length of slack comparable to the length of the secondary cable from which the pilot weight hangs at a set distance below the mouth of the main core barrel. Upon deployment the pilot weight will make contact with the seabed first, releasing the tension on the secondary cable which triggers the quick release on the primary core barrel and wire. This allows the barrel to free fall with the slack from the primary wire cable and to penetrate the seabed. The piston is held in place at the seafloor by the primary wire cable and so is drawn up the barrel as the barrel penetrates the seabed. Upon retrieval using the primary wire cable the pulling force on the piston maintains suction in the core barrel which helps to retain the sample, however, a core-catcher fitted to the mouth of the barrel is an additional means of preventing sample loss[33,35,36].

An advantage of this arrangement is that there is a prescribed distance above the seafloor from which the primary corer is supposed to freefall that is consistent over successive coring attempts. This is in contrast to simpler gravity corers, for which distance from seafloor must be estimated by comparing vessel-measured water depth with deployed wire cable length. The better constrained drop-height of a conventional piston corer will lead to more consistent sampling and therefore better sample precision compared with gravity corers. The piston coring system eliminates the risk of an operator underestimating the depth to the seafloor and accidentally lowering the corer directly into the seabed with the break-enabled wire cable, resulting in poor penetration and possibly ‘double-stabbing’ of the seabed if there is a significant amount of uncompensated heave from the vessel transmitted down the wire at the time (as can occur with other ‘over-the-side’ coring systems).

Conventional piston corers suffer from very similar drawbacks to gravity corers in that good sample recovery is generally limited to relatively soft, fine-grained, cohesive sediment. This means they cannot be deployed for representative sampling in other types of ground conditions. They are similarly liable to damage if they encounter hard substrates or obstacles. Consequently, conventional piston corers seem to have taken a back-seat in modern seabed mineral exploration programmes. That said, conventional piston corers are utilised widely in the research environment and, in amenable ground conditions, are capable of penetrating the seabed to significant depths. The giant piston corer 'Calypso' developed aboard the French research vessel the R/V *Marion Dufresne* can be fitted with a tube up to 75 m long and has been able to recover a world record 64.4 m of sediment from a single deployment[35].

Automated Core Sampling Tools

Vibrocorers

Vibrocorers (see Figure 1d) typically consist of a tripod-supported housing containing a vibrating head that is driven by hydraulic, pneumatic, mechanical or electrical power and which uses vibrating energy and the force of gravity to drive a core barrel into the seabed. Once penetration is complete the 'vibrahead' is turned off and the core barrel is withdrawn back into the housing using hoist equipment[37] (however some variants are capable of vibrating during retrieval)[38]. The whole apparatus is then retrieved using a winch and wire cable.

The vibration of the core barrel (or 'tube') has an amplitude of a few millimetres and a vibration rate of 3,000 - 11,000 vibrations per minute. This causes a thin layer of material to mobilise along the inner and outer walls of the barrel, reducing overall friction and allowing the barrel to penetrate the sediment more easily than other types of corers. A one-way core catcher fitted to the entrance to the barrel helps to prevent suction generated in the hole during retrieval from drawing core back out of the barrel[37].

While the vibrating motion can enhance penetration capability it can also negatively impact on the preservation of the core by causing greater disturbance to the substrate than conventional drop-corers. However, their generally more sophisticated core catchers means that vibrocorers, though by no means perfect, are generally better at retaining non-cohesive sediment samples than other, simpler coring systems[39,40].

A problem with vibrocorers (and potentially all other corers) is that despite the vibrating motion, increasing wall friction inside the tube as sediment enters the barrel can exceed the bearing strength of the sediment, causing it to stop moving up the barrel. This causes the barrel to temporarily behave like a solid rod rather than a hollow tube, forcing its way down through sediments without actually collecting further core ('rodding'). This can result in the loss of intermediate layers of sediment, which may be very difficult (or impossible) to detect in the recovered cores[37]. Such samples are therefore not representative and will show poor precision due to the inconsistency in recovery as well as the generally small diameter of the core sample. They will also be biased and have poor accuracy due to the loss of sediment. 'Rodding' can be prevented by utilising a core catcher with a smaller internal diameter than the core barrel. This allows a layer of water to exist between the incoming core and the inner wall of the core barrel which acts as a lubricant allowing core to more easily progress up the barrel as the barrel penetrates the seabed.

Another problem with vibrocorers is that whilst the reduced friction during coring allows them to more easily penetrate into sediment, the lack of vibration during retrieval in some variants means friction with sediment surrounding the core barrel is greater than during coring. In very cohesive sediment this can lead to equipment becoming stuck in the seafloor[41]. Other corers can encounter similar problems in very cohesive 'sticky' sediment where their penetrative force and speed is greater during coring than during retrieval. Pulling too hard on the wire cable in attempts to free embedded equipment can result in damage to components, implosion of core barrels (in deeper water), loss of sample and/or the loss of equipment overboard[41].

Though most commonly utilised in shallow water settings[42], vibrocorers can be used in water depths of up to 6,000 m[43] and in ideal situations can provide good recovery and continuous sampling over several metres of sediment. Best recovery occurs in unconsolidated, moderately cohesive, silty and heterogeneous sediment of mixed grain size[37]. In these latter environments data from vibrocorers may be useable for mineral resource estimation, if the process of collecting the data is well controlled by suitable SOPs.

Vessel-Mounted (Surface) Drilling

In contrast to other sampling techniques, drilling involves motorised and continuous sampling during which time the performance of the equipment is adjusted by an operator as sampling (typically coring, but recently also reverse circulation rock chip collection[44]) progresses. Once drilling is underway the operator can monitor progress and adjust different parameters as ground and other drilling conditions change—namely the speed of rotation of the drill string and drill/core bit, the thrust (weight-on-bit), and the flow rate of drilling fluid to the bit (necessary to cool the bit and remove drill cuttings)[39]. All of these parameters must be carefully monitored and controlled to optimise drilling progress without unacceptable loss or disturbance of core or unnecessary wear or damage to any of the numerous components that comprise a drilling system.

Vessel-mounted drilling into the seabed was pioneered by the oil and gas industry. However, in general, oil and gas drilling involves very little preservation of the material being drilled[39] as sufficient information can be gathered from evaluation of drill cuttings. While cuttings and other non-core materials are also useful for solid mineral explorers (see RC drilling below) oil and gas industry drilling techniques have been adapted by seabed researchers and the solid seabed minerals industry to improve core preservation and recovery, so as to gain greater geological and structural information. This is sometimes referred to as ‘coring’ (using an open drill bit through which core passes and is collected in a core barrel) as opposed to non-core producing ‘drilling’ (using a closed drill bit with no core barrel) to differentiate the two fundamentally different objectives and drilling assemblies they require. The expense of seabed drilling in general means most solid mineral explorers engage in ‘coring’ to maximise the amount of data that can be gathered from a drill hole. Consequently, ‘drilling’ and ‘coring’ are often used in the same context by different sources.

Early advances in marine drill ‘coring’ (hereafter simply referred to as ‘drilling’) were made by international collaborations of scientific researchers, mainly the Deep Sea Drilling Project (DSDP, 1966-1983) and Ocean Drilling Program (ODP, 1983-2003)[45]. More recently the Integrated Ocean Drilling Program (IODP, 2003-2013) and International Ocean Discovery Program (2013-ongoing) continue to develop vessel-mounted seabed coring technology[39,45].

Vessel-mounted drilling is a significant undertaking, with most systems requiring a large, specially designed vessel equipped with a moonpool (a hole through the deck and hull of the vessel housing a funnel-shaped guidehorn through which the drill string passes) and a dynamic positioning system that can maintain the vessel’s position despite the effects of wind, waves and ocean currents[39,46] (see Figure 1i). A drillship must also be fitted with a heave compensator so that consistent weight-on-bit can be maintained, allowing drilling/coring into the seabed to progress effectively despite the continuous heave, pitch and roll of the vessel (and rig floor) at the sea surface[39,47]. Limited compensation can also be made for movement of the vessel out of geographical position[48].

Vessel-mounted drilling can potentially have hundreds of different configurations depending on the size, type and design of numerous different critical and optional components. Different configurations will have a direct influence on the quality and reliability of core that is collected. Two of the most critical factors to be taken into account are the internal diameter of the drill pipe and the configuration of the bottom hole assembly (BHA). These form the primary constraints on the size and type of core barrel (and downhole tools) that can be deployed in any one hole. The diameter of the core barrel in turn constrains the maximum diameter of core that can be collected, and therefore the volume and precision of core samples. Several other fundamental components, such as the type of drill bit, have a first order influence on the quality of core that can be recovered. The drill bit cannot be changed (in the majority of cases) without recalling the entire drill string (a 'pipe trip') to change the BHA configuration, and so this must be carefully optimised for the specific ground conditions being drilled prior to a hole beginning, to maximise drilling efficiency and collect samples of the desired quality[39].

Most core drilling methods utilise a wireline system that enables successive core barrels to be deployed (usually by free falling down the drill string) and retrieved by a wireline cable at the end of each coring run. This saves a significant amount of time between coring runs compared to conventional drilling, which would otherwise require a pipe-trip each time a core barrel needed to be retrieved—something particularly time-consuming with the long drill strings required in deeper water and/or in deeper holes. Additionally, leaving the drill string in a hole between runs can help maintain hole stability and prevent a hole from collapsing, which may contaminate samples or prevent further coring[39].

Drilling can be conducted with an 'open hole', allowing cuttings to accumulate on the seafloor (a 'total loss' system), or with more sophisticated systems that utilise a riser to transport cuttings back to the drillship. Seawater can be used as the main drilling fluid or alternatively drilling mud can be used which can help improve hole stability[39] and is critical in non-cohesive formations in order to reduce the possibility of hole collapse. As drilling fluid is lost to the surrounding seawater during 'open hole' drilling, where drilling mud is used in such cases it should be a biodegradable variant.

A number of coring tools and methods can be employed, including rotary core barrel (RCB), extended core barrel (XCB, ESCS), motor-driven core barrel (MDCB), and diamond core barrel (DCB) systems[39]. RCB is more reliable than other systems for coring indurated sediments and hard rock, but final trimming of the core is done by a rugged drill bit with a thick kerf (i.e. the ratio of bit diameter to core diameter is high). This means core is more roughly cut and sediment samples more disturbed than those recovered using other drilling methods. The IODP developed the XCB to limit such core disturbance. It uses an extended core barrel positioned ahead of the main drill bit to trim core before the larger diameter, more rugged drill bit drills over the top. In theory the system ought to provide better core preservation, but as well as collecting smaller diameter, lower precision samples, it has numerous issues, particularly with poor fluid circulation at the barrel tip resulting in ineffective drilling or the inability to drill at all[39]. MDCB is an optimised version of the XCB, but has its disadvantages in that the drilling operators receive very little feedback as they adjust flow rates of fluid down the drill string and cannot tell whether changes are improving drilling conditions at the bit or not. This makes the MCDB hard to operate, and also results in slower coring than other drilling systems. Despite these shortcomings the MDCB has proven to be the only tool used by the IODP that is capable of recovering hard-soft interbedded sediments with minimal core disturbance[39]. These deposit characteristics are notorious for providing difficult drilling conditions and are commonly encountered around SMS deposits.

Diamond drilling has long been recognised by land-based drilling specialists as the most efficient and effective means of drilling whilst also retrieving good core recovery and preservation, particularly in hard rock. Unfortunately it does not easily translate into an effective system at sea as diamond drilling is conducted with a thinner drill pipe that relies on contact of the drill string with its own hole walls to maintain lateral stability—something that can't be done if the drill string is operating in several tens or thousands of metres of water. Similarly, while diamond-impregnated bits are potentially very much more efficient at cutting core, they require much greater rotation speeds and much greater control of weight-on-bit, which is difficult to maintain at sea without a very effective heave compensation system[39].

Despite these drawbacks, some success has been achieved with diamond drilling using 'piggyback' drilling systems that nest one drill string inside another. This involves an outer drill string penetrating the upper seabed, attached by hydraulic clamps to a weighted guidebase deployed on the seafloor. The weight of the guidebase assists with heave compensation and the clamps ensure the top of the drill string maintains the same distance from the seafloor. This provides a stable casing through which a second drill string can be run, operated from a secondary ('piggyback') heave-compensated drilling platform that functions very much like a land-based diamond drilling rig. The outer drill string maintains lateral stability of the inner drill string, and can also act as a riser for drill cuttings and fluids[39,49]. While the piggyback system is generally capable of good core recovery (provided ground conditions are amenable), running two drill strings requires double the amount of equipment that would otherwise be needed to drill a hole and therefore, while it can be highly effective in shallower waters (<200 m)[50] may become prohibitively expensive to employ at greater depths, depending on ground conditions and drilling efficiency.

Vessel-mounted drilling is susceptible to all of the problems encountered by land-based drilling. These include (but are not limited to): power failures, a drill string becoming stuck in a hole and/or getting bent or damaged[46], failure of the wireline to latch onto the core barrel for retrieval[46], core loss through a malfunctioning or inappropriate core catcher, blocked drill/core bits[39,46], crushing, splitting or other failure of the core/tube liner (reducing core preservation and recovery)[39,46], and of course, general wear and fatigue-related failure of all components[39]. Vessel-mounted drilling is further susceptible to additional problems related to operation in an oceanic environment. No heave compensation system is perfect and there is always residual movement causing variations in weight-on-bit that can lead to ineffective drilling or damage to the BHA components[39]. A fault or failure of a vessel's dynamic positioning system can cause a drillship to move off-site, forcing a deployed drill string against the guidehorn of the moonpool and potentially causing damage to both. Another problem encountered with some systems is that extraction of a core barrel and wireline from a long, well-sealed drill string can lead to the air-water interface within the drill string being several tens of metres below the keel of the drillship. If a fresh core barrel is allowed to free fall from the rig floor to this depressed interface, the force of the impact can cause the core liner to explode. Such core liner failures can severely impact core preservation and recovery. This particular failure can be prevented by ensuring the drill string is full of water (or drilling mud) before deploying each core barrel[39]. Pumping drilling fluid in between coring runs can also ensure the drill bit is clear and that the next core barrel will correctly latch on to the BHA.

The full range of practical challenges facing vessel-mounted drilling operators varies depending on the ground and sea conditions, as well as the limitations of the equipment they have at their disposal. Ultimately the sampling objectives of any drilling campaign will determine which of these challenges can be ignored and which must be overcome to recover core samples of the desired recovery and preservation. Drilling with poorly configured or poorly operated equipment can lead to very poor recovery and result in costly sampling campaigns that yield unreliable and non-representative sample data, particularly if samples are required of sufficient quality to be used in resource estimation[27]. While minimal core disturbance is ideal, if disturbed core (or even cuttings) can be retrieved that amount to consistently good recovery throughout the seabed profile and which can be reliably pinpointed to specific depths or depth-ranges within an accurately surveyed hole, core samples will be representative of the mineralised profile and, with reliable sample preparation and analytical techniques, provide accurate and precise samples.

Operators aiming to establish a mineral resource using vessel-mounted core drilling data are encouraged to seek involvement of a Competent Person early in the process so that the correct constraints on quality and reliability can be established and so that suitable SOPs can be prepared *before* drilling commences.

Seabed (Subsea) Drilling

As seabed mineral exploration advanced into deeper waters it became advantageous to have drill rigs that could be operated from the seabed rather than from a drillship. In principle, seabed drilling is conducted with the same methods and operationally equivalent components as other drilling methods (and faces most of the same challenges), but with the obvious exception that drill string handling is conducted on the seabed by robotic machinery controlled by an operator at the sea surface (via an umbilical tether)[47] (see Figure 1j). This isolates drilling from vessel movements and subsequently enables critical drilling parameters such as weight-on-bit to be more precisely controlled and thin-kerfed, diamond coated or impregnated drill bits used to maximise drilling efficiency[47,51]. Remotely operated seabed drilling has the potential to save the time and equipment required to otherwise run a drill string through several hundred (or thousands) of metres of water to begin drilling a hole, especially if additional pipe trips are necessary during the progression of a hole. The comparative lack of deck-based manual handling of seabed drilling equipment also makes for a potentially safer working environment for crew on deck[47].

Seabed drills can be launched from vessels of opportunity that are not in themselves specially designed drilling vessels. Such vessels must, however, have a large amount of free deck space (in the order of several hundred square metres) to accommodate the seabed drilling apparatus, its launch and recovery system (LARS) and often one or more ROVs that are used to monitor and troubleshoot drilling progress. This equipment has substantial mobilisation costs, although most developers have designed their equipment to pack down into standard-sized shipping containers to try to minimise mobilisation expenses. While being remotely operated means seabed drills can be less expensive to operate than vessel-mounted drills, large crews are still required to operate as well as deploy and retrieve the equipment from necessarily large vessels. Where operated from smaller vessels with smaller crews the vessel may have a smaller window of operability in than a larger vessel, which may impact on overall drilling efficiency[48]. Consequently, seabed drilling can prove more expensive than surface drilling in terms of the final cost-per-metre of core that is recovered[52].

Early seabed drills operated as conventional drilling systems, but these allowed a lot of material to fall back down the hole and contaminate subsequent cores, potentially negatively impacting on sample representativeness where contaminated material cannot be identified and omitted. Consequently, conventional drilling typically utilises casing to maintain hole stability during drill string retrieval and redeployment and, where successfully automated, can avoid sample contamination. Alternatively, wireline systems have been developed that enable a drill string to be left in the hole between drilling runs. This limits the chances of contamination and potentially saves on drill string handling time in deeper holes[53] however it introduces the additional possibility of the core barrel failing to latch on to the BHA.

Seabed drilling systems are capable of drilling and storing more core by having built-in rod racks or carousels to house additional drill pipe, casing and core barrels. The number of these a system can house determines the maximum penetration depth of the rig, which is currently around 150 m[54,55]. While this is significant and likely sufficient for practical seabed mineral exploration, it is not comparable to the penetration depths that can be achieved by vessel-mounted drill systems (the deepest offshore drilling on record is by the scientific research drillship *Chikyu* which has drilled to 2,466 m below the seafloor in 1,180 m water depth[56,57]). Seabed drills can operate at significant water depths in excess of 5 km[58], beyond the practical limits of most vessel-mounted drilling operations, however, most seabed drills operate effectively down to ~3,000 m water depth[48].

Some seabed drilling systems utilise ROVs to provide power and to manoeuvre the rig into place[59,60], however, attaching the ROV to an otherwise un-powered seabed drill can be challenging in an oceanic environment where everything is constantly moving. The majority of systems currently available have their own dedicated electric motor and operate hydraulically. They are lowered into position by a dynamic positioning-capable vessel and several use additional thrusters to help manoeuvre the rig into final position on the seabed[51]. Depending on hole depth, multiple short holes can be drilled in different locations during a single deployment by lifting the apparatus a few meters off the seabed and towing it to the new drill site[51]. This can improve drilling efficiency for closely spaced holes[47] and also allows for better control on sampling precision by making the collection of duplicate drill holes easier. Adjustable legs enable the systems to level and stabilise themselves on the seafloor, on slopes up to ~30°[58]. Some systems have extended legs that distribute the weight of the rig further from the actual collar point of a hole, minimising disturbance to any very soft sediments on the seafloor prior to drilling commencing[47].

Several systems have integrated rotary coring and piston coring (and in some cases vibrocoring[43]) capabilities to optimise penetration and recovery of hard rock and unconsolidated sediment, respectively[47,54]. Such systems typically also have a range of other downhole testing capabilities[47,55]. While integrated piston and drill coring increases the chances of good core recovery in variably hard and soft ground conditions, as mentioned previously, such systems will still experience poor recovery in difficult ground conditions, such as where hard-soft interbeds occur on a scale that is smaller than the run length of a core barrel. Consequently, core recovery, representativeness and precision may be poor in such formations, and the samples biased. Reports on average core recovery of seabed drills vary, with some quoting average recoveries of 80%[61], and others reporting this value as an average maximum recovery and average recovery generally between 10% and 80%. Figures vary depending on several parameters but tend to be lower in difficult ground conditions or where a crew change leads to inexperienced personnel operating equipment[27]. Such figures are suboptimal in terms of representative sampling. In the cases of poor recovery, the sampling data would not be useful for mineral resource estimations.

Most drilling systems have difficulties recovering the uppermost, unconsolidated sediments of the seafloor, which is not ideal if mineralisation is present at the surface and not recovered, leading to biased sampling. Similarly, drill coring in general, produces cores of small diameter and so all drill core suffers from low sample volumes being recovered for any one horizon, even when overall core recovery is good. This is particularly true of some seabed drills that utilise narrow core barrels to save on weight and maximise the number of barrels they can accommodate (however, some seabed drilling systems routinely recover cores of greater diameter than vessel-mounted drilling systems). While small core diameter is not necessarily a problem in deposits with a low degree of grade heterogeneity, it may dramatically reduce the precision of sampling in more variable deposits that have a high intrinsic grade variability.

Drill String Piston Corers

While vessel-mounted and seabed drill systems are the only methods capable of penetrating hard rock and consolidated horizons, drilling can cause an undesirable amount of disturbance and loss of recovery in softer, unconsolidated sediment. Piston corers can collect comparatively undisturbed samples in soft sediment, and consequently the piston coring concept has been adapted to enable piston core barrels to be deployed and retrieved on a wireline within a drill string, interchangeably with other types of core barrels depending on the level of sophistication of the system.

While there are numerous variations of individual components, the fundamental concept in vessel-mounted drilling systems comprises a piston-equipped core barrel held in place by a number of shear pins that are designed to fail under prescribed pressure. The piston core barrel is deployed and once seated in the BHA (at the base of the hole, ready to begin coring), the drill string is sealed and the hydraulic pressure inside increased to the point where the shear pins fail and the piston core barrel is ‘fired’ and rapidly propelled into the seabed while the piston remains in place[39,48]. Conversely, seabed drills with piston coring capabilities tend to simply push the corer into the sediment. The advantage of this over conventional piston coring is that successive piston core barrels can be deployed and retrieved to advance a single hole further into the seabed—up to several hundred metres where ground conditions are amenable[62].

Piston coring in soft sediment is capable of retrieving well-preserved cores with excellent recovery (when fitted with an appropriate core catcher), making them provide potentially more representative samples than other coring systems. In terms of recovery, piston corers are generally much quicker than drill coring in unconsolidated ground conditions[62] and therefore are also a more efficient method of sampling under these circumstances. Some systems are capable of producing oriented core or pressurised core, as may be required for sedimentary studies[39].

As the pressure used to fire the piston core barrel is designed to force it several metres into sediment, premature firing of the corer in seawater can severely damage the apparatus. Conversely, where sediment is stiff or a core barrel encounters hard rock, the pressure may not be sufficient for the piston core barrel to fully extend beneath the BHA. Retrieving such ‘partial strokes’ in some systems involves lifting the drill string until the scoping section of the core barrel is fully extended. This draws the internal piston the remaining distance up the core barrel while leaving the core barrel in place in the sediment. Suction generated by this motion can draw additional sediment or seawater into the barrel producing ‘false core’ or potentially liquefying the real core. Modified systems have been developed to prevent this, comprising valves that enable seawater to enter the barrel above the core but below the piston post-firing and so eliminate suction during retrieval of partial strokes[39]. Competent Persons wishing to use data from piston corers in mineral resource estimations should investigate which method is used to ensure optimal representativeness of their data.

The advantage of drill string piston coring is that it can be integrated with drill coring (and occasionally other methods of sampling) in a single hole. Piston coring and drill coring are capable of returning good recovery and relatively undisturbed core samples in soft sediment and hard rock, respectively, and consequently the combined approach offers explorers a more versatile method of sampling inhomogeneous seabed within a single hole. Incorporated into one interchangeable sampling system the methods have the potential to make overall hole coring more accurate and more representative of the actual downhole stratigraphy. One further benefit of the system is that the drill and piston cores tend to be approximately the same diameter, making the cores collected using the two methods more comparable in terms of sample support.

However, integrated systems, whether vessel-mounted or seabed drilling systems, still have their drawbacks. Small core diameter has the potential to bias samples of coarser grained sediment as very coarse grains may be pushed aside rather than drawn into the core barrel during sampling of unconsolidated sediment. That said, loose sediments typically pose more serious recovery challenges that will have a greater negative effect on the representativeness of the core. Integrated piston and drill coring will still experience poor recovery in difficult ground conditions, particularly where hard-soft interbeds occur on a scale that is smaller than the run length of a core barrel. This forces both methods of coring to attempt to penetrate and recover horizons that they are not suited to and will result in poor recovery and therefore poor accuracy and representativeness of the overall core recovered from such runs. Poor recovery also makes it very difficult to determine where the recovered core actually comes from within a run, meaning sample location accuracy down a hole may be poor. In such circumstances explorers can apply a conservative approach to core loss allocation whereby for the first run core loss is allocated to the start of the run due to soft sediment typically being lost at the start of drilling. For subsequent runs core loss may be allocated to the bottom of a run, except where it is possible to join core between runs and core loss may be allocated within a run based on visual inspection. Uncertainty can be reduced by drilling shorter runs but in the case of seabed drills this can limit the amount of core that can be drilled and recovered per dive.

Even with good recovery the precision of core sampling using a drill string piston corer may still be low in deposits with a high degree of intrinsic variability, due to the typically small diameter of cores that are collected. Since drilling capable of utilising piston corers is primarily conducted on polymetallic sulphide deposits, which are known to have variable grades and zoned mineralisation[27], this has significant implications for the drilling density required over such deposits to acquire enough sample data to mitigate the lack of precision in each sample. Those aiming to include such data in mineral resource estimations need to carefully assess recovery issues and make sure that SOPs are in place to deal with these issues *before* the data are collected.

RC Drilling

Reverse circulation (RC) drilling is a highly efficient method of drilling that produces pulverised rock chips as opposed to preserved core. The method utilises an outer drill rod with an inner tube which, when connected together into a drill string, provide a sealed pathway up the inside of the overlapping tubes. In land-based settings high-pressure air is forced down the annulus formed between the drill rods and the inner tube pathway. This drives the drill bit (typically an RC hammer or a blade or tri-cone roller bit) which grinds up the rock material into cuttings that are transported to the surface by the circulating air travelling back up the inside of the sealed inner tubes[63]. This reduces the likelihood of contamination from wall rock from other parts of the hole and therefore produces more representative samples than other chip-producing drilling methods that do not utilise an inner tube chip-return pathway (such as rotary air blast (RAB) drilling)[64]. RC samples are therefore generally reliable, as long as their depth of origin is well constrained.

A further advantage of RC drilling is that it can achieve high levels of recovery (and therefore more representative samples), even in unconsolidated or friable ground where other methods of drilling struggle to recover core (such as hard-soft interbeds). These benefits have seen the RC drilling method be adapted for seabed exploration. Several systems are currently under development for both surface and seabed drilling applications[50,65] and an RC rig has already been used for resource definition drilling of at least one offshore mineral resource (shallow water iron sands[44]).

General Seabed Sampling Challenges

While each sampling method has its own intrinsic strengths and weaknesses, there are a number of challenges that must be overcome by them all to successfully sample the seabed, and most relate to the fact that sampling is conducted very far removed (up to and in excess of 5 km) from the point of operation of the sampling equipment.

The vast majority of systems utilise a wire cable or tether for deployment and retrieval from the sea. Most systems are therefore susceptible to winch failures and cable entanglements that can lead to sampling failure or loss of sampling equipment, as well as potentially dangerous situations for crew on deck. For this reason larger sampling systems may have custom-built cages to restrict their movement on deck[12], and more complex systems, particularly seabed drills, have their own dedicated LARS[43,55]. As water depth increases deployment and retrieval times for all wire cable sampling systems are unavoidably increased, reducing sampling efficiency for deposits in deeper water.

All the systems discussed are operable in a range of water depths; however, the deep seabed is under pressures significantly greater than atmospheric pressure at the surface. Deploying equipment without enabling trapped air to escape can result in damage (and in extreme cases implosion) of the apparatus[5]. The change in pressure as samples are retrieved can also lead to the expansion of gas bubbles in cores, leading to core disturbance or core expansion, potentially resulting in core liner failure and/or inaccurate measurements of core recovery[39].

Cameras are now commonly employed on various sampling systems, including chain-bag dredges[5], bucket-grab samplers[66], box core samplers[5,18], and seabed drills [67]. Not only does this enable optimisation of equipment use by allowing operators to see how systems are performing in real-time and adjust their sampling procedure accordingly, but it also provides a valuable record of the seabed environment immediately prior to sampling (the 'before' case). This can be compared to 'after' sampling images to assess the environmental impact of the sampling procedure, as well as the overall effectiveness of the sampling procedure[39]. It is good practice to include the use of TV cameras in SOPs as they provide a key quality assurance tool to the sampling method.

DISCUSSION

An overview of the various sampling methods discussed is in Table 1 and Figure 2. Table 2 presents the general characteristics of the

Table 1: Summary of seabed sampling methods

Method	Description	Variations	Complexity	Relative Cost	Sampling Efficiency[1]	Seafloor Penetration[2]	Sample Volume[3]	Sample Quality[4]
Dredge sampling	collector deployed on a cable & dragged along the seafloor behind moving vessel	chain bag with (or without) reinforced opening; pipe	Simple	Low	Moderate	Surface Only	Small - Very Large	Poor
Bucket-grab sampling	hinged apparatus with opposing jaws that close in an approx. semi-circular fashion, enclosing sample	free-fall (float or wire retrievable); mechanical, pneumatic or hydraulic powered closure; partially or completely enclosed	Simple - Moderately Complex	Low - Moderate	Moderate - High	Shallow	Small - Large	Poor - Very Good
Box core	an open-ended square/ rectangular 'box' driven into the seabed under its own weight; 'shovel' arms close the box; retrieved using winch & wire cable	single or dual-closing shovels; weights can be added to improve penetration	Simple	Low	Moderate - High	Shallow	Small - Moderate	Poor - Good
ROV grab sampling	remotely operated vehicle (ROV) requiring a launch and recovery system (LARS) uses one or more manipulators ('arms') to break off pieces of rock	numerous depending on the size and configuration of the ROV	High	High	High	Surface Only	Small - Moderate	Very Poor
Gravity core	core barrel free falls under its own weight & penetrates the sediment; retrieved using a winch & wire cable	weights can be added to improve penetration	Simple	Low	Moderate - High	Shallow - Deep	Small - Moderate[5]	Poor - Good
Conventional piston core	trigger mechanism releases a core barrel housing a piston which advances up the barrel as it penetrates the seabed; retrieved using winch & wire cable	barrel size and additional weight chosen depending on desired penetration depth	Simple - Moderately Complex	Low - Moderate	Moderate - High	Shallow - Very Deep	Small - Moderate[5]	Poor - Very Good
Vibrocore	core barrel is driven into the seabed under own weight enhanced by vibration energy; retrieved using winch & wire cable	hydraulic, pneumatic, mechanical or electrical vibrating head	Moderate	Moderate	Moderate	Shallow - Moderate	Small	Poor - Good
Vessel-mounted drilling	moonpool-equipped vessel deploys a drill string to the seafloor; directly controlled by operators on rig floor of the vessel	conventional or wireline drilling; open hole or riser drilling; rotary, extended barrel, piggyback diamond coring etc; numerous configurations of different components	Complex	High	Low - Moderate	Shallow - Very Deep	Small - Moderate[5]	Poor - Very Good
Seabed drilling	robotic drilling system remotely controlled by an operator on deployment vessel	most systems operate from an umbilical; ROV or self-powered rigs; dedicated or multi-function drilling-coring-testing systems	Complex	High	Low - Moderate	Shallow - Deep	Small - Moderate[5]	Poor - Very Good
Drill string piston coring	pressurising a drill string causes a piston core barrel to fire into the seafloor	dedicated piston core systems; multi-function systems integrated with vessel-mounted or seabed drilling rigs	Complex	High	Moderate	Shallow - Very Deep	Small - Moderate[5]	Poor - Very Good

Notes: 1) relative ability to collect more samples over shorter periods of time; 2) loosely differentiated as shallow (<1m), moderate (~1-10 m), deep (~10-100 m), very deep (>100 m); 3) samples volume recovered for any particular horizon; 4) high quality samples are loosely considered as those that are most representative with high accuracy and good precision; 5) refers to core diameter.

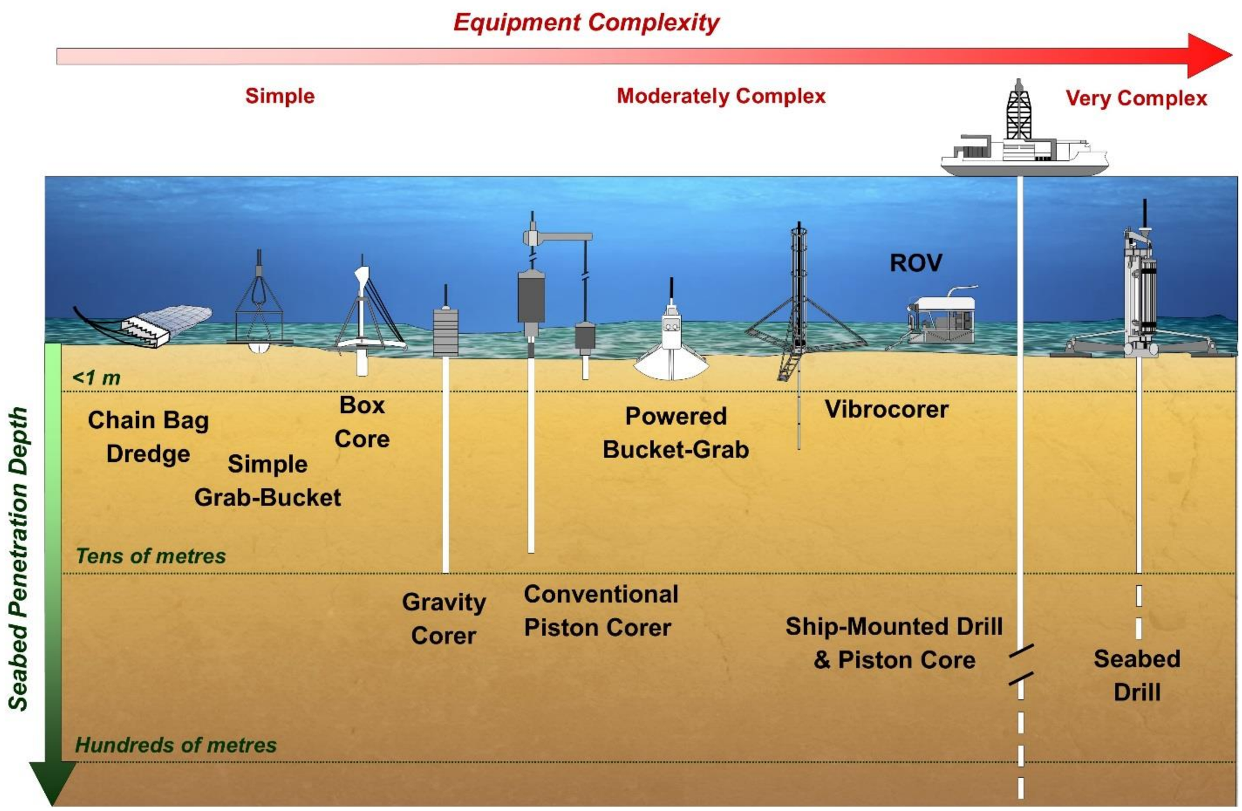

Figure 2: Seabed sampling methods (not to scale).

various sampling systems in terms of the critical parameters of sample *accuracy*, *precision* and *representativeness*. Most non-drilling sampling systems operate best in soft, unconsolidated yet still cohesive sediment and experience moderate to poor recovery in other ground conditions. There are no coring methods that consistently achieve good recovery in loose, non-cohesive sediment. Bucket-grab samplers and box core samplers are most effective at sampling such sediments provided that the sand or gravel concentration is low in comparison to the silt and clay components. The apparatus must also be vented and their closing mechanisms able to fully seal the grab bucket or box upon closure to prevent sample loss upon retrieval. Box core samplers collect a more representative sample than bucket-grab samplers in this instance, as bucket-grab samplers have an inherent bias toward sampling the shallowest sediments. Both systems have limited penetrative capability (sampling the upper <1 m of the seabed). Vibrocorers are arguably the best option for achieving good recovery in unconsolidated sediments from greater penetration depths below the seabed.

Drilling (surface or subsea) and other coring methods are required to penetrate deeper into the seabed. Gravity and conventional piston corers are able to penetrate several tens of metres into soft sediment, but drilling is the only option for penetrating and collecting intact core from hard rock and consolidated ground. Homogeneous, consolidated ground is also where drill core recovery tends to be highest. Seabed drilling is generally the preferred option in deep water (>1000 m) due to sampling efficiency gains made by not having to retrieve core barrels to the sea

Table 2: Accuracy, precision and overall representativeness of sampling methods.

Method	***Accuracy*** *sample recovery & lack of contamination*	***Precision*** *sample volume c.f. deposit variability*	***Representativeness*** *collection of unbiased samples*	***General Comments***
Dredge sampling	Very Low *(poor penetration; fines & very coarse material excluded)*	Moderate *(high volume samples)*	Very Low *(poor material & location accuracy)*	Good for reconnaissance sampling of unconsolidated surficial sediments; has been used to collect bulk-samples (non-representative).
Bucket-grab sampling	Moderate - Very Low *(consistently biased sampling of uppermost material)*	High - Very Low *(higher with larger bucket-grabs)*	Mod. High - Very Low *(better in larger versions with assisted closure)*	Standard equipment for sampling seabed nodules despite consistent bias toward sampling uppermost sedimentary horizons.
Box core	High - Very Low *(poor penetration in coarse and/or cemented substrates)*	Mod. High - Low *(generally small volumes; sampling area ≤0.5 m^2)*	High - Very Low *(poorer penetration & smaller volume than large bucket-grabs)*	Standard equipment used widely for seabed surface sampling and for nodules resource definition.
ROV grab sampling	Very Low *(surface sample only)*	Very Low *(poor sampling consistency)*	Very Low *(biased toward easily accessible samples)*	Unreliable sample quality, but only method known of sampling polymetallic sulphide 'chimneys'.
Gravity core	High - Very Low *(lower where poorer penetration and/or greater core loss)*	Moderate - Low *(moderate - small core diameter)*	High - Very Low *(highest in soft, cohesive sediment)*	Standard equipment, not used as extensively as bucket-grab or box core samplers; has been used for resource definition sampling on at least one project.
Conventional piston core	High - Very Low *(lower where poorer penetration and/or greater core loss)*	Moderate - Low *moderate - small core diameter*	High - Very Low *(highest in soft, cohesive sediment)*	Standard sampling equipment similar to gravity corers. Capable of excellent penetration and good sample preservation in soft, cohesive sediment.
Vibrocoring	High - Very Low *(lower where poorer penetration and/or greater core loss)*	Low *(generally small core diameter)*	High - Very Low *(highest in soft, cohesive sediment)*	Typically shallow water deployment, but reported use down to ~6,000 m water depth.
Vessel-mounted (surface) drilling	High - Very Low *(poor recovery in non-cohesive or mixed hard-soft ground)*	Low - Very Low *generally small core diameter*	High - Very Low *(highest in hard rock or consolidated sediment*	Technology adapted from established oil and gas industry and land-based drilling methods. Ongoing development, particularly by research-oriented campaigns. Only alternative to seabed drilling to penetrate hard rock and consolidated sediments. Only option for drilling to several hundreds of meters below the seafloor.
Seabed (subsea) drilling	High - Very Low *(poor recovery in non-cohesive or mixed hard-soft ground)*	Low - Very Low *(generally small - very small core diameter)*	High - Very Low *(highest in hard rock or consolidated sediment)*	High-tech robotic drilling systems under ongoing development. Potentially highly efficient and cost effective, particularly at greater water depths. Penetration depth below the seafloor currently limited to ~150 m. Only alternative to vessel-mounted drilling to penetrate hard rock and consolidated sediments.
Drill string piston coring	High - Very Low *(poor recovery in hard or non-cohesive ground)*	Low *(generally small core diameter)*	High - Very Low *(highest in soft, cohesive sediment but low precision)*	Innovative systems available capable of retrieving quality cores, particularly from cohesive, heterogeneous silty, mixed-grain size sediment. Wireline systems capable of quickly penetrating several hundred meters of sediment through multiple runs.

surface and return them to the seabed again after every run. The penetration depth of seabed drills is, however, limited in comparison to vessel-mounted drilling. Conducted from a stable seabed platform, drilling has the potential to provide better core recovery and preservation than vessel-mounted drilling[58], although the fundamental parameter influencing core recovery is the nature of the ground being drilled and both seabed and vessel-mounted drills will struggle to recover core in suboptimal ground conditions. Recovery can be improved through the use of appropriate drilling muds in place of seawater as the primary drilling fluid, however, this is only in the early stages of development for seabed drilling systems and has yet to be optimised.

'Rodding' or 'core blocking' can occur in all coring tools when increasing friction between the core and core barrel results in the temporary prevention of movement of the core, causing the barrel to behave like a solid 'rod' rather than a hollow tube and pushessediment aside as it advances rather than collect further core. The resulting 'lost' horizons can be very difficult to detect in the recovered core, which will not be representative of the full stratigraphic profile penetrated by the barrel. 'Rodding' during drilling may be determined when a run length exceeds the length of a core barrel, however, it may still be unclear where core is missing and what depth the missing core corresponds to, especially if drilling recovers expanding clays that may compensate for lost core or lead to over-recovery. Conversely, a lack of recovery may be due to vugs or cavities within deposits, however, these may be identified by drilling parameter data such as a reduction in weight on bit at depths corresponding to poor recovery[26,68].

All sampling methods struggle to recover interbedded hard-soft horizons, such as unconsolidated volcaniclastics and pelagic sediment interbedded with hard basalt lava flows, as is commonly associated with polymetallic sulphide deposits[39,52]. Integrated drilling and piston coring systems offer the most versatile approach to sampling in this kind of ground as drilling can be utilised to penetrate the hard horizons and piston coring to more efficiently penetrate the soft horizons whilst also (generally) providing better recovery in sediments. The success of integrated systems may still be limited, especially where horizons are thinly bedded (i.e. beds thinner than the length of a single drill or piston core run). In such cases a prior understanding of ground conditions can be critical to choosing the best sampling approach. This can generally only be developed after an initial phase of sampling has already been undertaken to gain a better understanding of the nature of the deposit. In any case, it is important to discuss with the drilling operators that emphasis must be placed on good recovery rather than on maximising metres drilled.

Recovery of samples from nodular deposits varies greatly depending on the size and distribution of nodules compared to the size of the sampling equipment used. No system currently in use (and reported in the public domain) has yet demonstrated reliable effectiveness at sampling ferromanganese crust deposits which require significant force to penetrate but are only thin (≤25 cm) surficial deposits. All sampling systems rarely if ever achieve 100% recovery, even in optimal ground conditions and consequently the majority of seabed samples will be not be suitably representative.

Another factor influencing sample accuracy is the extent to which samples remain uncontaminated. Hole collapse during drilling can lead to contamination and false core being recovered by subsequent runs. Wireline drilling with casing, particularly riser drilling utilising drilling muds as the primary drilling fluid, can enhance hole stability, however, hole collapse is still a risk and may result in equipment becoming stuck in a hole and/or core being contaminated. Similarly, suction generated from retrieval of ‘partially stroked’ piston cores, where the ‘fired’ core barrel did not fully penetrate the seabed, can result in the addition of ‘false core’ drawn into the barrel from the bottom of the hole. Alternatively suction in some systems can draw in seawater that can liquefy true core and cause it to be more easily lost through the core catcher upon retrieval.

Recovery and sample contamination are the key variables when determining the representativeness and accuracy of samples. This is something that must be carefully assessed on a per-sample basis and documented at the time of sample collection, to determine the level of confidence that can be assigned to each sample for subsequent geological modelling and resource estimation purposes.

Gravity-, piston- and vibrocorers can be effective at sampling the upper several metres of soft sediment seafloor, while drill coring and integrated drill core and piston coring can penetrate hundreds of metres into the seabed. However, the volume of the recovered sample in coring systems is comparatively small, meaning that samples retrieved from such tools have poor precision, especially in deposits that have a high intrinsic natural variability. For such deposits either much larger samples must be taken to obtain appropriate levels of data precision, or many more samples collected at a closer sample spacing to mitigate the lack of precision. This has important implications for the size and type of sampler chosen for any deposit. Larger and/or more sophisticated samplers are more expensive and logistically challenging to operate, and consequently have lower sampling efficiency than smaller samplers. It must also be taken into account that the more complicated or difficult equipment is to use within its intended operating constraints, the harder it will be to maintain consistency during sample collection, resulting in less precise sample data (i.e. ‘sampling error’). This poor precision is *in addition* to the natural intrinsic grade variability for the deposit being sampled. Careful scoping of a project needs to be undertaken in such cases to determine the most cost-effective and acceptable trade-off in terms of financial cost, time and desired sample quality.

The Theory of Sampling (TOS)[69] requires that every part of a unit of rock, sediment or ‘core’ to be sampled (commonly termed ‘the lot’ in the TOS) must have exactly the same chance of becoming part of the sample. Therefore, towed, grab and spot sampling tools are intrinsically flawed methods of sampling and should not be used in estimation of a mineral resource. However, some nodule and crust deposits can be treated as two-dimensional and in these cases some spot sampling techniques may be appropriate, but only if they are carefully controlled by good SOPs.

Whilst methods such as bucket-grab samplers and box core samplers can be effective at sampling unconsolidated surficial sediments, both can run into difficulty where surfaces consist of consolidated sediment, hard rock, or are composed of closely-spaced coarse grained nodules forming an effectively impenetrable ‘nodule pavement’. In the latter case samplers may be retrieved that show every sign of having operated properly but which contain no sample. Under these circumstances the recent and widely used technique of deploying sampling equipment with TV cameras attached proves an invaluable quality assurance tool in determining whether, for example, a locality consists of solid, non-mineralised rocky outcrop (i.e. ‘zero grade’) or of densely packed nodules (very high grade) that may require sampling to be re-attempted using an alternative method with greater penetration power. How this process is managed has significant implications for subsequent geological and resource modelling.

Representativeness is also important when planning new or assessing legacy sampling programmes. Sample spacing and layout need to be adequate for the specific deposit, taking care not to oversample higher grade areas. This is an important issue to consider when assessing legacy data, because most legacy campaigns have focused on higher grade areas and estimation of a mineral resource based on such data will lead to a strongly biased estimate, especially if other accuracy and representativeness issues (discussed above) are not adequately taken into account. Geological features will control the mineralisation and sampling needs to be planned such that each geological domain is properly defined.

A critical issue faced by all seabed sampling systems is accurately determining the location of seabed sampling sites. This is more difficult at greater water depths where sampling is conducted up to several kilometres from the base of operations on board a vessel. Determining sample locations relies on a vessel's on-board navigational system and generally assumes that sampling takes place immediately below the vessel's position on the surface. The validity of this assumption can be crudely assessed by comparing the length of wire cable let out to the water depth determined from sonar, but at best this will provide an accuracy of several metres to several tens of metres relative to the vessel's location, even in comparatively shallow water (hundreds rather than thousands of metres depth).

The greatest influence on the accuracy of sampling locations is the accuracy of the vessel's positioning system, which, before the onset of GPS, has the potential to be out by several hundred metres (or even several kilometres). Most modern exploration vessels employ a dynamic positioning system that utilises surveyed beacons deployed on the seafloor to triangulate their position. Short baseline systems use hydrophones mounted on a vessel to triangulate their position relative to a (typically) single seafloor beacon. More accurate long baseline systems use a single hydrophone mounted on the vessel to triangulate the vessel's position relative to several beacons arranged in a precisely surveyed array on the seafloor[39]. Such acoustic positioning systems can also be used to accurately pre-determine the desired collar point of a drill hole on the seabed and to locate the sample collection point of a sampling device equipped with a beacon. While these systems are potentially very accurate, beacon arrays take a long time (and therefore are expensive) to deploy, and positioning can still be thrown out by hundreds of metres due to seafloor topography interfering with acoustic signals[70]. The accuracy of sample locations is paramount for the estimation of a mineral resource and should receive suitable attention before sampling programmes are implemented.

CONCLUDING REMARKS

Representative, accurate and precise sampling is critical for reliable resource estimation[2] and the success of any subsequent mining initiatives. Ultimately the choice of sampling system(s) for a sampling campaign will depend on the desired outcome and the technological and financial limitations of the programme. No single system is capable of handling all ground conditions[40] and consequently the vast majority of seabed sampling suffers from suboptimal sample recovery, poor precision and poor accuracy. Obviously, maximum sampling efficiency is desirable, especially in light of the daily operational costs of seabed sampling vessels. However, sampling efficiency often comes at the cost of sample quality, particularly in terms of sample precision, which requires greater sample volumes and therefore larger sampling equipment that may be more difficult and time consuming to deploy.

For all sampling methods available and discussed in this paper, an operator should ensure that it has an adequate SOP in place to manage the quality of the sampling. If this is not available, a Competent Person cannot adequately assess the appropriateness and quality of the sampling and it will not be able to be used in any mineral resource estimation. The sampling SOP should be constructed with the input of the Competent Person *well before* the programme commences. It should make it clear to all involved, and at any level, how exactly each sample is to be collected. This is a critical requirement that often doesn't receive enough attention and ultimately leads to the requirement of expensive check sampling programmes to be carried out under controlled conditions to establish that indeed the original sampling was of suitable quality. The sampling SOP should also incorporate document quality control checks to ensure the reliability of sample data documentation.

When planning sampling programmes, it is critical for seabed explorers to have a good understanding of the ground and operating conditions they expect to encounter during sampling. This will allow them to thoroughly assess their sampling equipment options and determine the most appropriate sampling method which, for any particular deposit, will provide an acceptable balance of financial cost, time required and desired sample quality. Ultimately, customised sampling equipment may need to be developed to reliably (that is, precisely, accurately and representatively) sample any particular seabed solid mineral deposit[61] and indeed, many explorers are currently working with equipment providers to modify and develop new methods of sampling[26,52,70]. It is possible that systems more effective than traditional sampling techniques have already been developed but have not yet been publically reported. Whether now or in the future, optimisation of sampling methods will significantly enhance the quality of data collected and utilised to find and define deep seabed mineral resources in coming years.

Acknowledgements

The authors would like to acknowledge the invaluable advice, information and feedback they received from Ray Wood, Robin Falconer, Matthew Nimmo, Ian Stevenson, Steven Downey, Faye Nelson, Thomas Kuhn, Alex Pyne, Hermann Kudrass, Taras Shepel, Robert Goodden and Tony Halliday.

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