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Defining active, inactive, and extinct seafloor massive sulfide deposits

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ABSTRACT

Hydrothermal activity results in the formation of hydrothermal mineral deposits, including seafloor massive sulfide deposits, at oceanic spreading ridges, arcs, and back-arcs. As hydrothermal systems age, the mineral deposits eventually become severed from the heat source and fluid-flow pathways responsible for their formation and become extinct. The timescales and processes by which this cessation of activity occurs, and the resultant distinction between hydrothermally active and inactive deposits has recently taken on policy implications related to the potential issuance of exploitation leases for seafloor massive sulfide deposits by the International Seabed Authority in Areas Beyond National Jurisdiction. Here, we discuss the scientific rationale behind designating hydrothermal systems as active, inactive, or extinct, with the aim of applying a scientific underpinning to ongoing policy discussions, which often lack a common set of criteria and use the same descriptions for opposing phenomena. We apply the simple definition that active vent fields currently exhibit fluid flow above ambient seawater temperatures, inactive vent fields are not currently exhibiting fluid flow but may potentially become active again, and extinct vent fields are not expected to become active again. We suggest these terms can only be correctly applied at the vent field scale and define a vent field as a geologically continuous entity that may include both actively and formerly venting hydrothermal deposits. Finally, we propose criteria and techniques for determining activity and reasonably bounding the extent of a vent field for classification purposes.

1. Introduction

Hydrothermal vents are sites of fluid discharge on the seafloor that occur along or associated with submarine tectonic boundaries such as mid-ocean ridges and subduction zones. In these geological settings, magmatic heat sources beneath the seafloor drive convective circulation of hydrothermal fluids along permeable pathways in the crust such as faults and fissures (Fig. 1) [1]. If the hydrothermal vents are discharging high-temperature ($>\sim 250$ °C), metal- and sulfur-rich fluids, a seafloor massive sulfide (SMS) deposit may develop over time on and/or immediately below the seafloor from the precipitation and accumulation of metal-rich minerals that precipitate from the fluid when it mixes with cold seawater [1,2]. In rare places, where these geologically-favorable conditions persist for an extended period of time, these deposits can grow to be large enough and contain high enough concentrations of Cu, Zn, Au, and/or Ag to be potentially economically viable sources for these metals and targets for the emergent industry of deep-seabed mining [3,4]. Eventually, hydrothermal fluid venting at any given site will cease, and the site will become hydrothermally inactive and ultimately extinct. Currently, very little information is available for inactive or extinct SMS deposits. InterRidge maintains an online "Vents Database" of all known and inferred hydrothermal systems discovered to date [5]. The current version (v. 3.4) contains 707 individual records of "submarine hydrothermal activity", with only 54 of these records listed as "inactive". The paucity of documented inactive sites is largely because inactive deposits are difficult to find as they do not have an associated hydrothermal plume, the detection of which is the primary exploration tool for SMS deposits [6]. The scientific focus on *active* hydrothermal vent sites, which host unique chemosynthetic taxa and which are locations of scientific interest beyond the economic interest driving SMS exploration further contributes to the low number of known inactive sites [7–9]. However, there is an increasing focus on inactive SMS deposits driven by the possibility of marine mining.

In Areas Beyond National Jurisdiction (ABNJ), any mining of SMS deposits (also referred to as polymetallic sulfide deposits) will be managed by the International Seabed Authority (ISA). As the ISA moves closer toward finalizing exploitation regulations for mining in ABNJ, discussion of environmental considerations, including what

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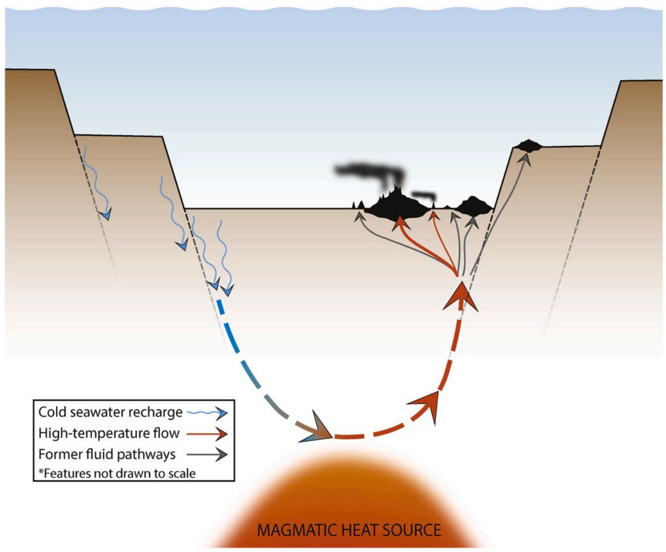

Fig. 1. Generalized schematic view of a typical hydrothermal system on a mid-ocean ridge. Fluid circulation is driven by a magmatic heat source and focused along zones of higher permeability, such as normal faults that occur within a ridge rift zone. A vent field, composed of active and inactive hydrothermal deposits (in black) forms where the fluids discharge into the oceans. Hydrothermal plumes form above active vents.

environmental protections are needed, has been a key component. A ban on mining of active SMS deposits has been suggested by parts of the scientific community, due to the minimal areas of the seafloor these vents occupy, their scientific value, and low estimations of their resource potential [10–12]. This has been followed by assertions that mining of active hydrothermal vents would likely take place in a limited manner, if at all, and that inactive deposits will be the main target of this emergent industry [13]. However, all current ISA exploration contracts include areas of active hydrothermal venting and, while only a fraction of each 10,000 km^2 exploration area will be subject to exploitation, a workable definition for active hydrothermal vents in a manner that could be legally applicable for mining regulations does not currently exist. Here we propose a classification similar to that used for volcanoes, which uses the designations *active*, *inactive (dormant)*, and *extinct*. We consider how this classification can be reasonably applied to hydrothermal systems and associated SMS deposits, in order to ensure a consistent and meaningful geologic framework for the evolving regulations. Known active hydrothermal systems are diverse, and many do not result in SMS formation. Here we discuss those associated with high-temperature sub-seafloor fluid circulation that has the potential to mobilize and deposit base and precious metals as sulfide minerals (e.g., temperatures above 250 °C) [14]. We specifically do not include systems that would not result in SMS formation, and so exclude low-temperature, low-flux systems associated with off-axis areas and seamounts.

2. Terminology

For clarity, we use the following terminology when referencing hydrothermal mineral accumulations on the seafloor at different scales (Table 1). Focused sources of high temperature hydrothermal venting typically emanate from *chimneys*, or individual, in places interlinked, vertical pipe-like mineral accumulations that have one or more orifices. Hydrothermal *edifices* or *mounds* are larger structures that form from the progressive accumulation of hydrothermal material on the seafloor at vent sites. Edifices and mounds are defined by their morphology, with edifices generally having steeper sides, and mounds having a distinct conical shape. Both structures may host chimneys. The spatial clustering of chimneys, edifices, and/or mounds on the seafloor define a *vent field*,

Table 1
Definitions for hydrothermal accumulations on the seafloor.

	Areal extent (m)	Description
Chimney	1–10s	Single hydrothermal vent or spire
Edifice	10s	Cluster of coalescing chimneys (e.g., Bastille or Dante edifices, Main Endeavour Field, Juan de Fuca Ridge)
Mound	10s–100s	Circular accumulation of hydrothermal material resulting in a "mound" morphology, often with a chimney cluster at its apex (e.g., active mound at TAG, Mid-Atlantic Ridge)
Vent Field	10s–1000s	A spatially associated cluster of chimneys or mounds that are linked by a common heat source and subseafloor permeability structure (e.g., Gondou Field, Okinawa Trough)

which describes a discrete region that contains hydrothermal accumulations distributed over an area with dimensions that can vary from 10s to 1,000s of meters (Table 1).

When referring to seafloor hydrothermal deposits as a resource, we use well-established language typically used by the land-based mineral resource sector (Table 2) [15]. If a seafloor hydrothermal site contains a spatially continuous accumulation of hydrothermal material of large enough size to be potentially mineable (i.e. a large edifice or mound), it is referred to as a *deposit* (e.g., the Solwara I deposit, in the Manus Basin) [16,17]. An *SMS deposit* refers to a subset of hydrothermal deposits that is composed dominantly of metal sulfide minerals (e.g., pyrite, chalcopyrite, sphalerite; note that the term *massive* in *seafloor massive sulfide* is a mineralogical textural term to indicate a mass abundance of sulfide minerals of $>\sim$60% and is not a reference to deposit size) [18]. Therefore, the term *SMS deposit* should be applied only to large accumulations of hydrothermal minerals (*deposits*) that are known from sampling or other methods to be composed largely of massive sulfide material. In other words, although every SMS deposit is a hydrothermal deposit, not every hydrothermal deposit is necessarily an SMS deposit. Petersen et al. [4] estimated that, at probable minimum ore grades (e.g., ~5 wt% Cu, 15 wt% Zn, 5 ppm Au), an SMS deposit would have to be at least 2 Mt to be an economically viable target for mining. This would correspond to a massive sulfide mound with a basal diameter of approximately 200 m and height of 60 m, similar to the active TAG mound [19]. Using these definitions, a vent field may contain no deposits, a single deposit, or several deposits, some or all of which may or may not be SMS deposits. Volcanoes are informally classified as *active*, *dormant*, or *extinct*, where an active volcano has erupted in the past ~10,000 years, a dormant volcano has not erupted in the past 10,000 years, but is expected to erupt again, and an extinct volcano has not erupted in the past 10,000 years, and is not expected to erupt again [20]. This classification can serve as a guide for the activity of vents fields, where active fields will contain hydrothermal venting at temperatures above ambient seawater, inactive vent fields lack apparent activity but were recently active, remain near a heat source, and have the potential to become active again, and venting is unlikely to resume at *extinct* vent fields. The classification of a volcano as dormant, rather than extinct, is normally due to the presence of indicators of heat and/or magmatic activity in the subsurface, such as seismic events within the volcano, elevated heat flow, or presence of fumaroles. Several examples of the eruption of an "extinct" volcano (e.

Table 2
Definitions used in the context of mineral exploration on the seafloor.

	Areal extent (m)	Description
Deposit	10s–100s	An accumulation of hydrothermal material on the seafloor of sufficient size that, with high enough metal grades, could be a potential mining target [15]
SMS Deposit	10s–100s	A subset of deposits that is composed primary of massive sulfide minerals (i.e. usually at least ~60% sulfide minerals; e.g., Solwara I deposit, Manus Basin)

g., Fourpeaked Volcano, Alaska) point to the lack of certainty associated with this informal classification, associated with an evolving understanding regarding deep-Earth processes. Likewise, the classification of a vent field as extinct should not be considered an absolute certainty, but instead a low probability that hydrothermal venting will reactivate in the future.

3. Indicators of hydrothermal activity

Defining an individual hydrothermal vent, deposit or vent field as active is conceptually simple enough: it is hydrothermally active when fluid with a temperature above that of ambient bottom water is venting from the seafloor. Hydrothermal plume surveys use CTD (Conductivity, Temperature and Depth) casts that also include optical sensors (turbidity) and sensors for chemical anomalies (e.g., salinity, Eh, CH_4) associated with the hydrothermal plume in the water column above and down-current from an active vent site, at distances of up to 100s of kilometers away from their source [6]. Collecting seawater on CTD casts also allows for the detection of ^{3}He, an unambiguous tracer of hydrothermal activity. Once a plume is detected, the hydrothermal site is typically visually located using a camera tow or cameras on a Remotely Operated Vehicle (ROV) or Autonomous Underwater Vehicle (AUV). Visual signs of venting may be obvious, with vigorous discharge of high-temperature black or white smoker fluid, often from multiple vents (Fig. 2A). Subsurface mixing of ascending hydrothermal fluid with local seawater prior to venting also typically occurs, and results in cooler, diffuse-flow fluids that may be shimmering due to temperature and salinity differences relative to seawater. Both "focused flow" and "diffuse flow" styles comprise active hydrothermal venting.

Even when venting is not visibly obvious, the presence of live hydrothermal vent-endemic species is another clear indicator of active venting. Vent biota have a tendency to colonize even the most diffusely venting, low-temperature sites, and, due to the vivid colors these organisms may display against a dull seafloor substrate, can be a particularly effective indicator of hydrothermal activity when fluid fluxes and/or venting temperatures are low (Fig. 2B).

On sites that have been sampled by dredge and therefore lack visual information regarding seafloor context, the presence of anhydride ($CaSO_4$) can be used as a mineralogical indicator of recent high-temperature hydrothermal activity and indicates that the site may still be active. Anhydrite precipitates when Ca-rich hydrothermal fluids mix with and/or heats up Ca- and SO_4-rich seawater at temperatures of above ~150 °C [21]. However, anhydride has retrograde solubility, and will dissolve back into seawater when it is no longer exposed to elevated temperatures. The rate of anhydride dissolution is not well constrained, and it is therefore not known for how long anhydride remains as a mineral phase within cold vent deposits. However, surficial areas of old, inactive or extinct deposits will not contain anhydride, although it may remain in areas not in contact with seawater (e.g., at depth) as it is found occasionally in volcanogenic massive sulfide deposits (VMS, i.e. the ancient equivalent of SMS deposits) [22].

4. Indicators of hydrothermal inactivity

There are several seafloor observations that indicate prolonged hydrothermal inactivity at a deposit or vent field and can therefore be important criteria for distinguishing inactive sites from extinct sites. Over long time periods (e.g., 1000s of years) it is likely that inactive chimneys will eventually collapse. The oldest known vent fields (e.g., >40,000 years old) are characterized by a notable lack of upright chimney structures, and instead are composed primarily of low-relief mounds (e.g., Peterburgskoe and Semyenov IV on the Mid-Atlantic Ridge) [23–25]. Chimney collapse occurs due to increasing structural instability as chimneys grow taller, the dissolution of thermodynamically unstable minerals in seawater, and because most hydrothermal systems occur in seismically active areas where ground motion can lead to collapse. However, timescales for chimney collapse may vary for different deposits according to tectonic and oceanographic setting (i.e. intensity and frequency of seismic activity; temperature and dissolved oxygen content in bottom waters), and the mineralogy and morphology of the deposits.

Oxidation of sulfide minerals within hydrothermal deposits indicates exposure to seawater. Oxidation begins as soon as the minerals are in contact with oxygenated seawater and thus oxidation occurs even during periods of active venting. Likewise, the dissolution of anhydride begins once the precipitated mineral is no longer hot, and therefore dissolution can occur on cooler parts of otherwise high-temperature vent structures. Prolonged periods of exposure to ambient, low temperature seawater can lead to substantial oxidation of sulfide minerals and anhydride dissolution, and both processes may be considered qualitative indicators of deposit aging, with the important caveat that these transformations do not *a priori* indicate inactivity. However, over long time periods loss of these minerals may fundamentally reshape hydrothermal deposits.

Inactive vents display an absence of chemosynthetic fauna and, if they have been inactive for long enough, will often host deep-sea slow growing sessile taxa such as sponges and corals (Fig. 2C). For a more detailed description of biological indications of activity and inactivity see Van Dover [26].

When applied independently, the indicators of inactivity described above (lack of upright chimneys, extensive oxidation, and lack of vent biological communities) may not necessarily be diagnostic for classification of inactivity on their own. However, taken together, these observations provide a reliable, unambiguous indication of prolonged hydrothermal inactivity.

5. Defining hydrothermal activity at the vent field scale

Although hydrothermal inactivity may be described at the scale of individual vents or deposits using the criteria in the preceding section, defining a *vent field* as active, inactive, or extinct is much more complex because we do not yet fully understand the spatial scale of hydrothermal circulation cells in the sub-seafloor. A vent field is generally described as a cluster of hydrothermal vents or deposits on the seafloor. The size, morphology, and distribution of hydrothermal deposits that make up a vent field can vary significantly, largely according to tectonic environment, making a simple definition based on deposit size or footprint impractical [2]. We use the concept of *geological connectivity* to define the extents of individual vent fields based on a common magmatic heat source and subseafloor permeability structure, such as normal faults or detachment faults associated with rifting along mid-ocean ridges, or ring faults associated with caldera collapse within arc volcanoes [27–29]. Using this definition, any spatially associated currently or formerly active vent sites and associated chimneys, edifices and/or mounds that are geologically connected would be considered part of a single vent field. Each vent field would be subject to a single classification of activity that would apply to the entire field, and any active vent field may contain more than one hydrothermal circulation cell. The evaluation of geological connectivity at a specific site would be possible by interpretation of geological features on the seafloor (e.g., faults, volcanic centers) identified through ship-based and high-resolution bathymetric mapping (e.g., ~40 m and 1 m resolution, respectively). These datasets would commonly be generated as part of any exploration and resource evaluation program.

The Endeavour Segment of the Juan de Fuca mid-ocean ridge provides an illustrative example of defining the limits of individual vent fields using the concept of geological connectivity. The Endeavour Segment is described as containing five major active vent fields that occur along 15 km of the ridge axial valley, each separated by 1.5–2 km, with several smaller fields, and other sites of diffuse venting occurring near or between the major active fields (Fig. 3A) [30]. However, this current clustering of active venting represents only a present-day

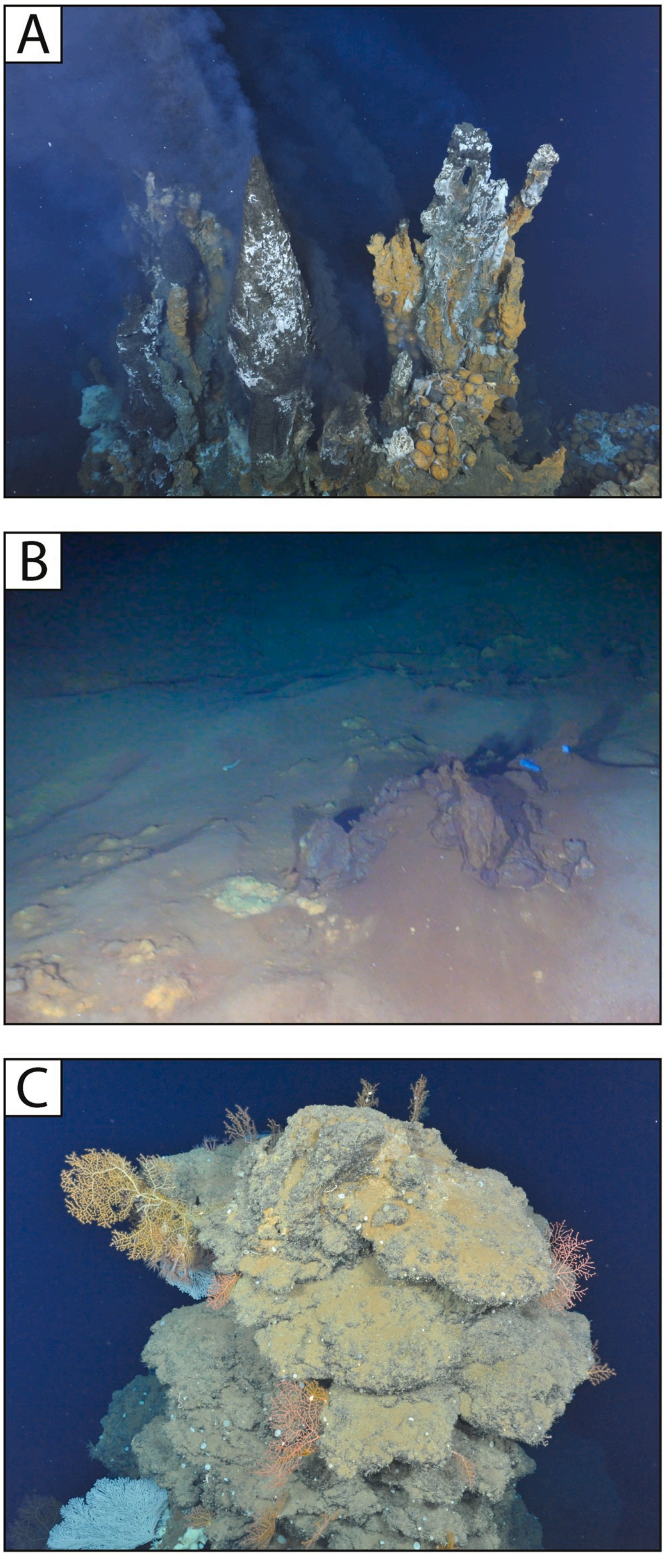

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Fig. 2. A) Active black smoker vents from the Niua South vent field, Tonga. Image captured using the ROV ROPOS during the Virtual Vents cruise on the R/V Falkor, courtesy Schmidt Ocean Institute. B) Yellow bacterial mats on the summit of Southern Mound, in the TAG hydrothermal field, Mid-Atlantic Ridge. The presence of bacterial mats suggest that hydrothermal fluid is still discharging from this mound that otherwise appears to be inactive. Photo captured by the HyBIS RUV, courtesy B. Murton, National Oceanography Center, Southampton, UK, funded through the European Union Seventh Framework Programme Grant No. 604500 (EU-FP7) 'Blue Mining: breakthrough solutions for the sustainable deep-sea mining value chain' C) Inactive chimney from the Endeavour Segment, Juan de Fuca Ridge. A prolonged period of inactivity allowed for non-vent-endemic sessile organisms to colonize the chimney. Photo captured using ROV ROPOS, courtesy Fisheries and Oceans Canada and the Canadian Scientific Submergence Facility. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

snapshot of the evolution of hydrothermal circulation along this 15 km length of ridge segment. This stretch of ridge axis also contains over 400 inactive chimneys, edifices and mounds that occur outside of the active vent fields and record over 3000 years of spatially and temporally dynamic venting at Endeavour (Fig. 3A) [31,32]. Seismic imaging along the ridge axis reveals that this venting was, and continues to be, driven by a continuous axial magma chamber beneath the ridge segment [33]. The vents occur in close proximity to the along-axis normal faults that define the axial valley and are likely an important control on subsurface permeability and hydrothermal fluid flow. Thus, although the active vent clusters each likely represent currently discrete hydrothermal circulation cells, the entire 15 km length of axial valley represents a geologically continuous zone of present or recent hydrothermal venting, driven by a common heat source and structurally controlled permeability regime. Endeavour should therefore be considered as a single continuous vent field, and, consequently, since parts of Endeavour are hydrothermally active, the entire 15 km long vent field should be considered active.

The five Semyenov vent fields associated with the 13°30' oceanic core complex on the Mid-Atlantic Ridge provide a contrasting example to Endeavour. Semyenov 1-5 are roughly equally spaced along the axis of the core complex (Fig. 3B) [34]. Apart from Semyenov 3 and 5, which are closely spaced and are geologically similar, these vent fields have different morphologies, compositions, and local tectonic controls and substrates. All vent fields are separated by stretches of substrate that show no indication of past hydrothermal activity. Here, it is appropriate that each vent field be considered as separate from the others, and individually classified as active, inactive, or extinct, as there is no indication of geological continuity between the five Semyenov fields (again, except for Semyenov 3 and 5, which should be grouped together). Based on extensive plume surveys and several ROV dives, only Semyenov 2 is known to be active, and Semyenov 1, 3, 4, and 5 appear to be extinct [35,36].

The TAG hydrothermal field presents a more challenging case study. The hydrothermal mounds that define the TAG field are distributed over a ~8 km^2 area on the eastern edge of the axial valley (Fig. 3C) [38]. Some of the mounds coalesce with adjacent mounds (e.g. Double Mound) or are directly next to each other (e.g., Shinkai Mound and New Mounds #2 and #3; Southern Mound and Rona Mound). Other mounds appear to be isolated deposits more than a kilometer away from other known mounds (e.g., Mir Zone, active TAG Mound, and Shimmering Mound). The TAG field has been used as a case study for the exploration for inactive deposits and understanding their physical and chemical evolution [37]. With the exception of the active mound, which is vigorously venting black smoker fluids, the mounds display characteristics of inactive deposits, including lack of venting or vent-related macrofauna, partial burial by sediments, paucity of upright chimney structures, partial dismemberment by faulting, and internal collapse, and Southern, Shinkai, and New Mounds have been described as "eSMS"

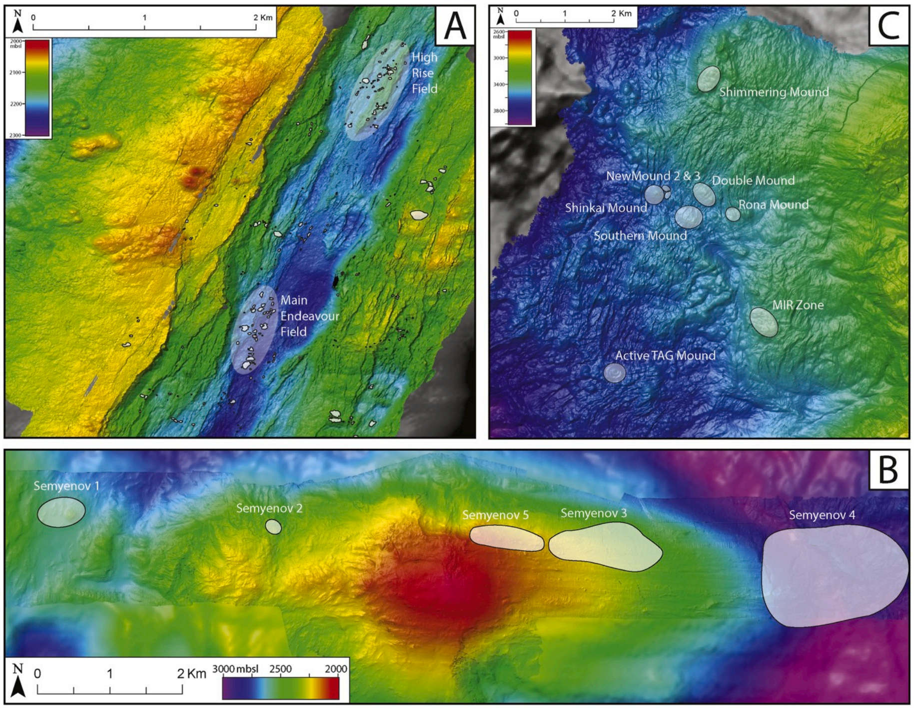

Fig. 3. Maps showing the diversity in scale and distribution of vent fields: A) Part of the Endeavour Vent Field, on the Juan de Fuca Ridge, which consists of a series of active vent clusters (referred to in the literature as individual "vent fields") and abundant inactive chimneys and mounds distributed along the axial valley. Individual hydrothermal accumulations (chimneys, edifices, mounds) are outlined in black. Modified from Ref. [31]; B) The five Semyenov Fields are located on an oceanic core complex on the Mid-Atlantic Ridge. In contrast to (A), the field outlines represent estimates of the extent of known hydrothermal deposition on the seafloor at each site, but not the actual deposit footprints. Vent field outlines are based on a combination of self-potential surveys [34] and ROV dive observations [36]. Modified from Ref. [36]; C) The TAG field, also on the Mid-Atlantic Ridge, consists of a cluster of hydrothermal mounds, distributed over am ~8 km^2 area. Modified from Ref. [37].

(extinct SMS) [37]. However, at Southern Mound, the presence of bacterial mats suggests that diffuse, low-temperature venting is occurring (Fig. 2B). The Shinkai and New Mounds lack evidence of bacterial mats, but host abundant upright chimney spires and do not display internal collapse features that characterize many of the other mounds. The lack of collapse features is interpreted to indicate that anhydride dissolution has yet to occur and heat is still retained within these mounds, suggesting that these mounds have only recently become inactive [37]. Radioisotope dating of hydrothermal precipitates indicate that large deposits form on the order of 1,000s to 100,000 s years [32,39–41]. Evidence from radioisotope dating of the active mound at TAG indicates that hydrothermal activity is cyclical, with prolonged periods of activity and inactivity [39], suggesting that, using the definitions proposed here, Shinkai and New Mounds may not be extinct but only currently inactive, whereas Southern Mound appears to be active. Overall, the cluster of mounds that define the TAG field are interpreted to have formed through hydrothermal circulation driven by a common ridge axis heat source and channeling of fluid along a common subseafloor detachment fault system [42,43]. Based on this interpretation, the entire vent field should therefore be classified as hydrothermally active, as the individual mounds are linked by the same underlying hydrothermal permeability structure.

The examples from Endeavour and TAG provide evidence that, although individual chimneys can in places be stable on decadal timescales, this is not universally true, and hydrothermal venting can be spatially variable over the lifespan of a vent field. Results from deep-drilling projects reveal that, in some places, drilling into the seafloor adjacent to an active black smoker does not intersect the system and results in no change to fluid flow in the active smoker. Drilling by ODP leg 169 at Escanaba Trough, a sediment covered spreading center, resulted in no intersection of hydrothermal flow nor changes to the adjacent active vent, less than 10 m from the drill site (Fig. 4A) [45,46]. In other places, however, drilling resulted in the creation of a new black smoker. In the Iheya North hydrothermal field, in the Okinawa Trough, for example, drilling adjacent to active hydrothermal vents during IODP Expedition 331 resulted in the formation of artificial, active hydrothermal vents, some of which persisted for more than 40 months and resulted in rapid hydrothermal chimney growth (Fig. 4B) [47]. Similar creation of artificial hydrothermal vents and associated chimneys were also reported during ODP Legs 139 and 169 at Middle Valley on the Juan de Fuca (Fig. 4C) [48,49]. At Iheya North, the fluids discharging from these artificial vents were higher salinity than those forming the natural hydrothermal vents in the region prior to drilling, as a result of segregation of high and low salinity fluids in the subseafloor, with only low salinity fluids venting in the absence of drilling [50]. This demonstrates that seafloor penetration in an active region may release not only fluids that are currently venting in other parts of the vent field but may connect with existing subsurface fluid reservoirs that are currently not venting. Given our current understanding of subsurface fluid flow, the dynamic and unpredictable nature of hydrothermal systems indicates that drilling into an inactive deposit in an overall active vent field has the potential to initiate fluid flow.

6. Global inventory of inactive SMS deposits

The InterRidge Vents Database is a researcher-driven compilation that aims to provide an international standard for documentation of all sites of submarine hydrothermal activity and includes both high-temperature "black smoker" ore-forming systems discussed here, and low-temperature systems associated with seamounts and fracture zones. Only 8% of the sites documented in the InterRidge database are classified as inactive [5]. Of the 54 sites classified as inactive, 36 are low-temperature systems that occur on seamounts (e.g., Brown Bear Seamount; Dellwood Seamount), Fe- or Mn-oxide deposits (e.g., Carlsberg Ridge, 1.67 S; Shikurose Bank), or disseminated sulfides in quartz veins in exposed crustal rocks (e.g., DSDP Hole 504B; Vema Fracture Zone) and are not considered high-temperature, ore-forming systems comparable to systems that could generate an SMS deposit and so are not considered here. Of the remaining 19 "inactive" sites, one site (Zenith-Victory, Mid-Atlantic Ridge) should be classified as active due to a report of a hydrothermal plume at this location [23]. Another "inactive" site from the Mid-Atlantic Ridge, Ashadze 4, is also not considered because the only published description of this site is a report of an inactive sulfide boulder with a maximum dimension of about 1 m that was observed and sampled during an ROV transect ~1.5 km downslope from the active Ashadze 1 field [52,53]. There are two sites classified as

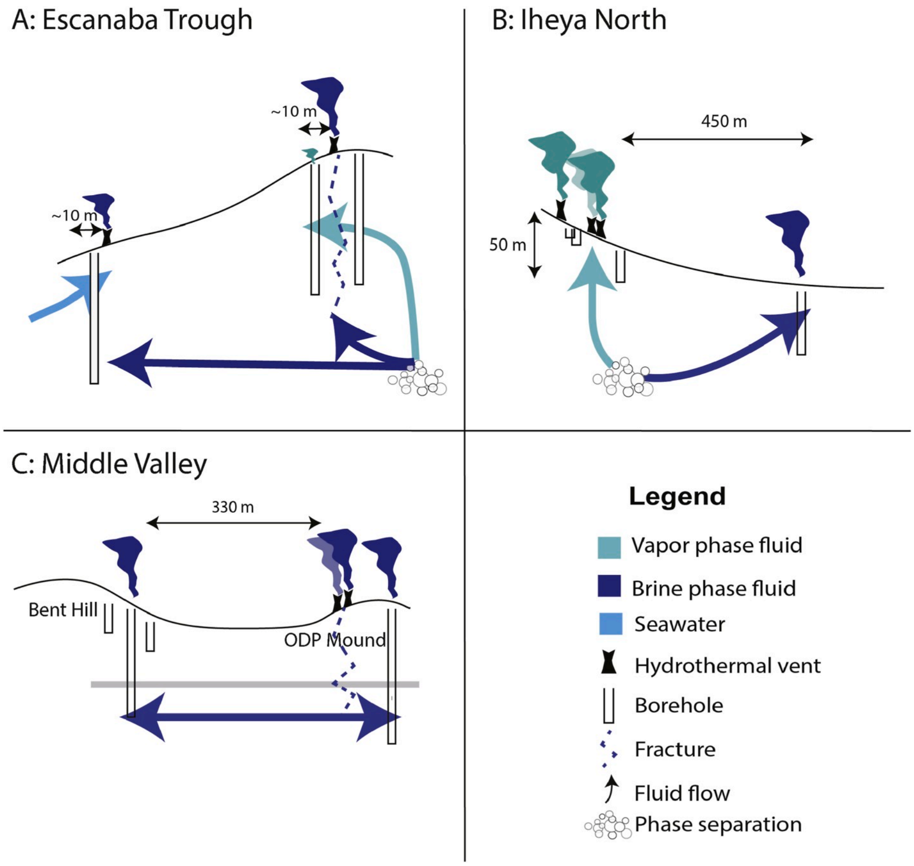

Fig. 4. The need to define hydrothermal activity at the vent field scale is illustrated by a current understanding of subsurface hydrothermal fluid flow, which demonstrates that system connectivity, and the definition of activity, are vent field-scale features. A) At Escanaba trough, Gorda Ridge, drilling within 10 m of a 218 °C chimney resulted in diffuse discharge of fluids with salinity lower than seawater; fluids emanating from the chimney had higher salinity than seawater and were unaltered by the drilling. A second borehole adjacent to a 108 °C chimney was interpreted to intersect a hydrothermal recharge zone. Rapid sedimentation in the trough complicates fluid-flow pathways, and the 218 °C chimney remained chemically stable for at least 14 years [46]. Although the majority of sulfide deposition in the trough is associated with either low temperature fluid flow, or past fluid flow, the hydrothermal field remains active. B) At the Iheya North vent field, in the Okinawa Trough, vapor-phase fluids were venting at an “active region” of the hydrothermal field prior to IODP drilling. Drilling approximately 450 m from the region of fluid venting intersected a hydrothermal fluid reservoir in a region of the field previously considered “inactive.” The fluids emanating from the borehole were brine phase, indicating segregation of the reservoir in the subsurface [50]. The presence of fluids below the seafloor that are accessed when new fluid flow pathways are introduced indicates that subsurface hydrothermal activity is not restricted to areas where there is currently fluid discharge. C) At Middle Valley, on the Juan de Fuca Ridge, drilling resulted in hydrothermal fluid flow within a borehole at ODP mound, where high temperature active hydrothermal fluid was already naturally discharging, and at Bent Hill, where limited hydrothermal activity was occurring prior to drilling. The deeper holes (>250 m) penetrated a silicified zone that was interpreted to be a cap rock [51]. The hot hydrothermal fluids underlie the active field, and venting occurs spatially where the silicified zone or cap rock is punctured by either fractures (i.e. existing vents) or drilling.

“inactive” for which we judge there to be not enough information for activity to be considered: the 24°N 30’ site on the Mid-Atlantic Ridge; and the site on the EPR 14 N Seamount that was discovered and sampled by a single dredge that recovered hydrothermal material [54]. Finally, there is a record for an inactive site at Mata Nima in the Lau Basin; however, no published record of hydrothermal vents, either active or inactive, can be found for this specific volcano.

Among the list of “active” sites in the InterRidge database are also sites that are known to be inactive. The Petersburgskoe site (Mid-Atlantic Ridge) is listed as “Active, inferred”, but no indications of activity at this field have been reported [23]. Also, “Semyenov” (Mid--Atlantic Ridge) is listed as a single record, yet as discussed above, represents a grouping of 5 vent fields, with Semyenov 2 the only active field. We know of two other inactive sites (Surprise and Yubileinoe, Mid-Atlantic Ridge; Bel’tenev et al., 2017) that are not yet listed in the database [55].

We therefore identify only 20 sites in the global InterRidge database that should be considered inactive using the criteria described above (Table 3). A detailed examination of all 707 records would be required to evaluate whether other potentially inactive sites are hidden or not individually listed in this dataset. However, from this initial analysis, the documented inventory of inactive deposits is very low, and points to 1) how little information we have on inactive deposits, including inactive SMS deposits; and 2) the need to improve our ability to locate inactive deposits.

Within the current inventory of inactive deposits that formed along mid-ocean ridges (i.e. excluding deposits that formed on seamounts) all occur within or on the flanks of the ridge axial valley (i.e. *on-axis*), which represents the neovolcanic zone, which can be tens of kilometers wide, and is associated with the locus of volcanic and hydrothermal activity along mid-ocean ridges [3]. For example, the Petersburgskoe deposit on the Mid-Atlantic Ridge is located on the western wall of the axial valley, 16 km from the ridge axis [23]; Lost City, on the Mid-Atlantic Ridge is 14 km from the ridge axis [8]; and the Penumbra deposit on the Central Indian Ridge is 14 km from the ridge axis [50]. As seafloor spreading continues, deposits that form on-axis will eventually migrate off-axis, and away from the heat source that drives the hydrothermal circulation. Off-axis deposits are therefore likely extinct, and attractive exploration targets for contractors. In fact, since all oceanic crust formed at mid-ocean ridges, the entire ocean basins may be prospective for extinct SMS deposits. The preservation of such deposits, which is likely controlled by the interplay of sulfide oxidation rates and burial by sediment or lava, will be a major factor in understanding the off-axis resource potential, although the abundance of VMS found in abducted oceanic terrains on land indicates that at least some fraction of these deposits is preserved.

7. Conclusions and implications for mining and exploration

The classification of hydrothermal activity, inactivity, and extinction

Table 3
Inventory of known inactive hydrothermal fields.

Name	Reference	Location	Latitude	Longitude
E Eye of Mordor	Anderson et al. (2006)	Galapagos Rift	1.906	−91.231
EPR, 13 N, SE Seamount	Hekenian et al. (1983)	East Pacific Rise	12.700	−103.860
Galapagos Rift, 85 50''W	Embley et al. (1988)	Galapagos Rift	0.750	−85.833
Green Seamount	Alt et al. (1987)	Northeast Pacific	20.803	−109.283
Krasnov	Bel'tenev et al. (2004)	North Atlantic	16.640	−46.475
Logatchev 4	Kuhn et al. (2004)	North Atlantic	14.706	−44.908
Logatchev 5	Cherkashev et al. (2000)	North Atlantic	14.750	−44.970
MESO Zone	Halbach et al. (1995)	Central Indian Ridge	−23.393	69.242
Mount Jourdanne	Fujimoto et al. (1999)	Southwest Indian Ridge	−27.850	63.933
Pere Lachaise	Auzende et al. (1991)	Southwest Pacific	−16.967	173.933
Solwara 12	Lipton et al. (2012)	Manus Basin	−3.709	151.883
Squid Forest	Pedersen et al. (1999)	Kolbeinsey Ridge	68.000	−17.500
Petersburgskoe	Shilov et al. (2012)	North Atlantic	19.867	−45.867
Semyenov 1	Cherkashov et al. (2010)	North Atlantic	13.514	−44.990
Semyenov 3	Cherkashov et al. (2010)	North Atlantic	13.513	−44.911
Semyenov 4	Cherkashov et al. (2010)	North Atlantic	13.506	−44.906
Semyenov 5	Cherkashov et al. (2010)	North Atlantic	13.511	−44.935
Surprise	Bel'tenev et al. (2017)	North Atlantic	19.875	−45.875
W Eye of Mordor	Anderson et al. (2006)	Galapagos Rift	1.970	−91.390
Yubileinoe	Bel'tenev et al. (2017)	North Atlantic	20.150	−45.745

that we define here is simple and geologically concise. Defining the extent of hydrothermal vent fields, which is necessary for delimiting the boundary to which a classification of activity would apply, however, presents a greater challenge. For the purposes of defining hydrothermal activity in relation to mining activities, it is important to note that, although mining will occur at the deposit scale, the geological connectivity that defines a vent field necessitates that the criteria used to classify the state of activity must extend beyond the limits of the deposit itself and be considered at the vent field scale. If an inactive deposit occurs within a vent field that is hydrothermally active (i.e. any regions within the field show evidence of activity or recently activity), the overall field must still be hydrothermally connected to its heat source, and all deposits within the field have the potential to resume activity. Therefore, deposits within an active vent field may be described as active or inactive, with the caveat that *inactive* sections of an *active* vent field may be expected to resume activity; and the classification of any deposit as *extinct* requires that the entire vent field be inactive and not geologically connected to any active venting. It is expected that any *extinct* hydrothermal field would satisfy the following three criteria: 1) absence of fluid discharge from the seafloor at temperatures above that of ambient bottom water; 2) a lack upright chimneys; 3) extensive oxidation of hydrothermal material; and 4) absence of live vent-fluid dependent biological communities.

Although designating areas or individual deposits within an overall active system as "active" or "inactive" may be biologically relevant over observed timescales, this approach lacks a connection to subseafloor processes and the validity of these designations may not persist when the subseafloor is disturbed by both natural events (e.g., magmatic or tectonic activity) and human modifications (drilling, mining). This emphasizes that such designations must take place at the vent field scale.

Our simple definition avoids ambiguities associated with other potential criteria for activity classification that would rely on continuous, non-discrete attributes such as vent fluid temperature or flow rates, and is consistent with an understanding of hydrothermal activity that at the primary level is defined by the presence of hydrothermal fluid flow. In the absence of a detailed sub-seafloor understanding of the plumbing of hydrothermal systems, including the dynamism of reservoirs, surface parameters are described that can indicate cessation of hydrothermal activity at the vent-field scale, including the lack of a hydrothermal plume and the absence of upright chimneys; as well as geological parameters that can be used to consider the extent of a vent field and differentiate geologically discrete fields on a ridge segment. Generally, fields on faster spreading segments exhibit more dynamic variability and fields on slow spreading ridges may be stable over thousands of years. However, indicators that hydrothermal activity can cease and restart, with hiatus lasting between less than one and several thousands of years, as well as begin in "inactive" regions of an active field as a result of drilling, demonstrate that we should label entire hydrothermal fields extinct with caution.

The implication of this binary geologic definition of activity is that, in the vast majority of cases where mineral exploration is occurring, both within EEZs and Areas Beyond National Jurisdictions, the main area of interest is an active hydrothermal field. However, the small number of known inactive deposits does not necessary reflect a low resource potential for inactive SMS deposits. Instead, it highlights our only cursory understanding of the distribution, preservation and ability to explore for these deposits. This provides abundant motivation for further research into the processes of SMS formation from hydrothermal fluids and reinforces the need to continue to explore the ocean basins, especially further away from the ridge crest.

CRediT authorship contribution statement

J.W. Jamieson: Conceptualization, Investigation, Writing - original draft. **A. Gartman:** Conceptualization, Investigation, Writing - original draft.

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