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A contemporary perspective on hadal science

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Highlights:

- Reviews contemporary technology and sampling effort at full ocean depth.
- Provides an overview of the recent acquisition of large ecological data sets.
- Details recent conservation initiatives and potential for biodiscovery.
- Provides key strategic sampling approaches to ensure continued progress in the field.

Abstract.

The hadal zone (6000 - ~11,000 m deep) arguably represents the last great frontier in marine science. Although scientific endeavour in these deepest ecosystems has been slow relative to other more accessible environments, progress is steadily being made, particularly in the last 10 years. This paper details the latest developments in technology and sampling effort at full ocean depth, scientific literature, representation in international conferences and symposia, the recent acquisition of large ecological data sets, conservation, the potential for biodiscovery and describes some key strategic sampling approaches to ensure recent progress is sustained effectively. The timing of this article is indeed to reflect on recent sampling efforts and resulting publications to provide perspectives on where the scientific community is with regards to hadal science and where it might lead in the immediate future.

1. Introduction.

Scientific endeavour of the world's deep-sea ecosystems has in recent decades rapidly emerging from an observational era to an experimental one (Tyler, 2003; Danovaro et al. 2014). However, our understanding of the lower-abyssal and particularly the hadal zones (>6000 m) are still more likely placed in the *early* stages of observation. This is in stark contrast to shallow and coastal seas where complex experiments have been on-going for more than a century. This is arguably due to the relative ease of access compared to deep environments that are notoriously more challenging. In shallow water ecosystems, the fauna and environmental correlates are more readily accessible for study, both *in situ* and in the laboratory; a luxury rarely obtainable in deep-sea research which is hampered by the great distances from shore, depths from the surface and hydrostatic pressure at depth. As a result, deep-sea sampling has lagged behind that of coastal and inshore research, a lag that is greater still in hadal science (Jamieson and Fujii, 2011).

A marine management paradox currently exists: we need to assess and protect the marine environment with the utmost urgency but we still know relatively little about it (Holt, 2010). Understanding marine biodiversity is a critical avenue towards the effective and sustainable management and stewardship of the oceans (Mengerink et al. 2014), however, recent studies highlight the stark realisation of the diminishing grasp of biodiversity with increasing depth (Rex and Etter, 2010); placing the hadal fauna as perhaps the winner of the 'least understood' award. In the past, ocean research has tended to focus on shallower habitats that were perceived to have a greater direct influence on day-to-day human endeavours. Deeper environments have historically not just been at the mercy of the technical challenges but also an anthropocentric opinion that the deep sea is a remote and enigmatic environment, far removed from everyday human activities ("out of sight, out of mind"). However, in the quest for 'Global marine stewardship and conservation' we must encompass the ocean in its entirety; from the atmosphere and air-sea interface to the deepest ocean trench, and therefore we must not simply ignore the deepest 45% on the grounds that it is really deep.

Recent efforts by international initiatives such as the Census of Marine Life (www.coml.org) have substantially advanced our knowledge of the marine diversity of specific regions and habitats on geographical and bathymetric scales hitherto unattempted (Snelgrove, 2010). Yet, despite the 10 year long project, it sadly did not include the hadal trenches and therefore, the knowledge chasm between the trenches and the rest of the ocean is ever widening. This is further illustrated in large data mining exercise such as Webb *et al*., (2010) who compiled a list of ~7 million records of marine organisms to provide an assessment of global marine biodiversity. This exercise highlighted the significance of 'chronic' under-sampling of the deep pelagic ocean exacerbated by its extraordinary large volume but overlooked the equally chronic underrepresentation of hadal fauna, presumably on account of the relatively low area coverage despite the enormous depth range that they encompass.

The irony here is that in 1956 Anton Bruun proposed the term ‘hadal’ to describe depths exceeding 6000 m derived from *Hades* (Bruun 1956), meaning both the Greek god of the underworld himself and the kingdom of the underworld, that can also be loosely translated as ‘the unseen’.

Efforts and progress in hadal science, particularly the biological sciences therein, are being made but historically have been extremely fragmented and have taken on quite different guises with each passing decade. Ever deeper samples were collected in the first half of the last century, leading to the extraordinary *Galathea* and *Vitjaz* expeditions of the 1950’s that arguably kick-started biological literature with the first ‘introduction’ paper by Wolff, (1960). The more modern, albeit short-lived, hi-tech exploration with the ROV *Kaiko* in the 1990s, preceded extensive use of free-fall landers in the last 10 years. These scientific endeavours have been punctuated twice by high profile media events; the *Trieste* (1960) and *DEEPSEA CHALLENGER* (2012) submersible dives to the deepest place on Earth; *Challenger Deep* in the Mariana Trench. There is good news though, hadal science is no longer at the mercy of technical challenges, and access to the deep subduction trenches is increasing at a reasonable pace.

We are now in an age where more countries are involved in biological research at hadal depths than ever before. Scientists from the US, UK, China, Japan, New Zealand and Denmark among others, are or have recently been actively sampling the deep-trench ecosystems. Coinciding with this progress are other significant events such as specific representation in International conferences (Jamieson and Fujii 2011; this issue), high profile exploratory missions (Gallo et al., 2015), a book dedicated to the subject (Jamieson 2015) and myriad of international media surrounding new scientific discoveries and, of course, the darker side of subduction, the earthquakes. All of these events collectively help to support and encourage a greater understanding and appreciation of hadal ecosystems.

The timing of this article is indeed to reflect on recent developments and hopefully provide some perspectives on where the scientific community is with regards to hadal science and where it might lead in the immediate future.

2. Technology and sampling effort

From a biological perspective, progress in sampling the hadal zone has been slow, originally hampered by the challenges associated with its sheer distance from the ocean’s surface. Equipment had to be lowered through thousands of metres of water, and before the onset of ship-mounted echo-sounders, simply measuring depth was an extraordinarily laborious task. The hadal zone is also challenging as a result of extremely high hydrostatic pressure: up to one tonne of pressure per square centimetre.

Despite these challenges, we now know the precise locations of the trenches and have made significant headway in understanding the biology and ecology of life in the deepest places on Earth, whilst having developed some sophisticated and innovative technology along the way. The myriad of technologies and methods adopted through the last 100 years are reviewed in Jamieson (2015), therefore hereafter will focus on current and very recent developments.

There are currently only a few vessels capable of bottom trawling to hadal depths, e.g. the German RV *Sonne* (Elsner et al., 2015), however, until very recent successes >6000m (Brandt et al., 2016; Linse and Schwabe *in press*), the last publication describing a hadal trawl or sledge sample for biological science was 26 years ago (Horikoshi et al., 1990), and was based on earlier (unspecified) trawls. Most modern research vessels no longer carry enough trawl wire in which to trawl at great depths, despite this being possible over 60 years ago (Kullenberg 1956). The ability to retrieve benthic specimens from extreme depths has not been replaced by more modern methods, but rather the last 20 years has seen a switch from mass physical sampling to largely visual sampling supplemented by discrete physical sampling.

There have only ever been a few large full ocean depth exploratory vehicles such as ROV/HOVs of which only one (ABISMO) is currently operational (Yoshida et al., 2009), following the loss of both ROV *Kaiko* and the HROV *Nereus* (Momma et al., 2004, Cressey, 2014 respectively) and the uncertain future of the *DEEPSEA CHALLENGER*. Some significant technological advances are on the horizon (Cui et al. 2013; Cui et al. this issue), and there are as yet unpublished reports of some Chinese groups being active in this field. However, there are still opportunities to obtain physical samples from the seafloor using baited traps (Fujii et al. 2013; Jamieson et al., 2013; Ritchie et al., 2015; Lacey et al., 2016), water samplers (Eloe et al., 2010; Tarn et al., 2016), sediment cores (Kitahashi et al., 2012, 2013; Leduc et al. 2015) but unfortunately trawling opportunities are still limited. Despite this apparent decline in major benthic sampling capability there has been a resurgence in hadal research in recent years (e.g. Jamieson et al., 2010; Cui et al., 2013, Gallo et al., 2015, Jamieson 2015) following the 60-year hiatus since the *Galathea* and *Vityaz* days (Wolff 1960, Belyeav, 1966). The resurgence in deep-abyssal and hadal research has largely favoured the free-fall 'lander' vehicle that descends to the seafloor, unattached to the surface vessel, and returns following the jettisoning of ballast weights by acoustic command. This method has become favourable for reasons such as financial risk to reward ratio (relatively inexpensive compared to ROV/HOV), a method relatively unaffected by depth (unlike trawling), and reasonably well-suited to the types of complex topography found in trenches. Landers have therefore led to a wave of observational studies (Hessler et al., 1978, Aguzzi et al., 2012; Jamieson et al., 2009ab, 2011ab, 2012ab, 2013), leading to ever increasingly large data sets (Linley et al., 2016, 2017), which when combined with baited traps have shown great progress in ecology (Blankenship et al., 2006, Blankenship and Levin 2007, Fujii et al., 2013, Lacey et al., 2016), and molecular studies (Ritchie et al., 2015, 2016, 2017, this issue). Water sampling landers for microbial studies are now also common place (Eloe et al., 2010, Nanoura 2015, 2016, Tarn et al., 2016).

Recent years has also seen the first ever biogeochemical experiments delivered to the trench floors. Glud et al., (2013), and later Wenzhöfer et al., (2016) deployed a lander-delivered oxygen microprofiling system to the deepest parts of three trenches (Mariana, Tonga and Izu-Bonin trenches) and measured benthic oxygen consumption for the first time and revealed extremely high O_2 consumption rates compared to the surrounding abyssal plains.

These technologies are of course only proven useful with the opportunities to deliver them to the trenches. Sourcing the funds to support the research expedition is often as difficult as funding the science and technology. However, by examining the number of research cruises reported in the literature since 2000, there is an emerging trend that in the last 10 years there are between 2 and 4 hadal research cruises undertaken annually, which is highly encouraging in consistency (Table 1).

Table 1. The Year, vessel name, trench and reference for hadal sea-going expeditions since the year 2000 (TF= Transform Fault)

Year	**Vessel**	**Trench**	**Reference**
2001	*Melville*	Kermadec/Tonga	Blankenship et al. 2006
	Hakuho-Maru	Kurile-Kamchatka	Kitahashi et al. 2012
2002	*Yokosuka*	Mariana	Kitazato, H, Pers. Comm.
2005	*Hakuho-Maru*	Ryukyu	Kitahashi et al. 2012
2006	*Pez Mar*	Puerto-Rico	Eloe et al. 2011
2007	*Sonne*	Kermadec/Tonga	Jamieson et al. 2009a
	Hakuho-Maru	Japan	Jamieson et al. 2009a
	Kairei	Mariana	Jamieson et al. 2009a
	Kairei	Izu-Bonin	Yoshida et al. 2009
2008	*Hakuho-Maru*	Japan	Fujii et al. 2010
	Kairei	Mariana	Yoshida et al. 2009
2009	*Tansei-Maru*	Izu-Bonin	Eustace et al. 2013
	Kilo Moana	Mariana	Fletcher et al. 2009
	Kaharoa	Kermadec	Jamieson et al. 2011a
2010	*Sonne*	Peru-Chile	Fujii et al. 2013
	Makai	Puerto-Rico	Leon-Zayas et al. 2015

	Yokosuka	Mariana	Glud et al. 2013
2011	*Kaharoa*	Kermadec	Jamieson et al. 2013
	Yokosuka	Japan	Oguri et al. 2013
2012	*Kaharoa*	Kermadec	Jamieson et al. 2013
	Promar'	Puerto-Rico	Søreide and Jamieson 2013
	Mermaid Sapphire	New Britain/Mariana	Gallo et al. 2015
	Yokosuka	Izu-Bonin	Wenzhöfer et al. 2016
2013	*Kaharoa*	Kermadec	Lacey et al. 2016
	Yokosuka	Tonga	Wenzhöfer et al. 2016
	Kaharoa	New Hebrides	Lacey et al. 2016
2014	*Thomas G. Thompson*	Kermadec	Linley et al. 2016
	Falkor	Mariana	Linley et al. 2016
	Falkor	Mariana	Unpublished
	Sonne	Puerto-Rico	Brandt et al. In press
2016	*Scientific Exploration 1*	Mariana	Unpublished
	Zhang Jian	New Britain	Unpublished
	Zhang Jian	Mariana	Unpublished
	Sonne	Kuril-Kamchatka	Unpublished
2017	*Shinyo-Maru*	Mariana	*Personal observation*
	Scientific Exploration 1	Mariana	Unpublished
	Sonne	Wallaby-Zenith TF	*Personal observation*
	Tangaroa	Kermadec	*Personal observation*

3. Large multi-depth and multi-trench studies

The first studies of multiple trench and large bathymetric sampling ranges arose from the *Galathea* and *Vitjaz* expeditions and emerged in the literature in the 1960s (Hansen 1957; Wolff 1960, 1961, 1970; Belyaev 1966; Vinogradov 1962, Vinogradova 1979). In the intermediate, many hadal papers, although highly valuable, tended to report on findings from a single trench, and often from a single depth within it (e.g. Hessler et al., 1978, Yayanos 1995; Perrone et al., 2002). Whilst this did supply new and fascinating insight, the approach constrained making any real progress on 'bigger picture' ecology. The last 10 years has seen an increase in the number of papers reporting from multiple depths across the depth range of trenches that permit depth related trends to be identified with some confidence (e.g. Blankenship et al., 2006; Jamieson et al., 2011a; Eustace et al., 2016). Further studies expanded this into performing standardised sampling across multiple depths over multiple trenches (e.g. Kitahashi et al., 2012; Fujii et al., 2013), and more recently several papers have been published with extensive data sets on a par with more conventional deep-sea studies, ranging from bacteria (Nunoura et al., 2015, 2016), to amphipods (Lacey et al., 2016) to fish (Linley et al., 2017).

Some studies are starting to address large scale phylogenies and population structure over multiple species, depths and trenches (Ritchie et al., 2015, 2017), and are starting to ask much larger questions with greater significance in a global context. One might argue that the true value in sampling at hadal depths is that it is likely to have great leverage on depth-related or geographic-related trends. For example, the study of amphipod *Eurythenes* spp. from the Peru-Chile Trench (Eustace et al., 2016) provided greater resolution to larger global studies of that genus with regards to disentangling bathymetric from geographic trends (Havermans 2016) and insights into how trenches can influence speciation. Likewise, hypotheses regarding the biochemical depth limit for bony fish (Samerotte et al., 2007), was not only proven using hadal snailfish (Yancey et al., 2014), it confirmed their absence in the bottom 3000 m (Linley et al., 2016).

Large data sets from bacterial studies are showing differences in free-swimming and particle associated microbes (Eloe et al., 2010) and are also revealing dissimilarities with more conventional deep-sea communities (Tarn et al., 2016). Nunoura et al., (2015) vertically profiled the microbial community of the water column from the surface to over 10,000 m and found a distinctive shift in pelagic communities across the abyssal- hadal transition zones. Interestingly, Jamieson et al., (2011a) indicated a potential ecotone across the abyssal-hadal transition zone in amphipod diversity, later expanded by Fujii et al., (2013). However, Lacey et al., (2016) examined a much larger dataset spanning three trenches and surrounding abyssal plains and confirmed such an ecotone at the abyssal-hadal boundary. Statistically it was best explained by pressure and food supply. Also, there was greater similarity between geographically closer trenches (New Hebrides and Kermadec) than one isolated by thousands of kilometres (Peru-Chile). The shift in pelagic communities of microbes reported by Nonoura et al., (2015) also included a greater number of heterotrophic taxa with depth, suggesting they likely metabolised locally recycled organic carbon, again suggesting a significant interplay between pressure and food supply, the latter of which is likely to accumulate at the trench axis (Ichino et al., 2015).

Building on the first series of *in situ* observation of hadal fish (Jamieson et al., 2009a, 2011a, 2013), Linley et al., (2017) not only confirmed another stark boundary between abyssal and hadal fish communities but also found a similar boundary in functional groups, specifically their mode of feeding: scavenging fish are largely absent from hadal depths in favour of predatory species.

The take-home message in the above examples is that there is an emerging body of consistent evidence to suggest that trends in hadal biology and ecology cannot always be extrapolated from shallower depths.

There is further added value in the collection of large hadal data sets, which is exemplified by Tarn et al., (2016) who discovered not only heterogeneity in microbe communities within different parts of the Mariana Trench (Challenger and Sirena Deep) but connections between the trench samples and subsurficial and vent-derived communities, particularly in the *Sirena Deep*. This suggests there may be unknown habitat heterogeneity, or direct connectivity with mud volcanoes and serpentine seeps, known from the area (Ohara et al., 2012; Feseker et al., 2014), adding further complexity to what we already poorly understand from an environment that we cannot readily predict theoretically.

Similar distinction are being made with regards to the importance of trenches in carbon cycling. Hadal trenches are considered to act as 'depo-centers' for organic material at the trench axis as suggested by Danovaro et al., (2003) and modelled by Ichino et al., (2015). This should therefore support an elevated community biomass relative to adjacent abyssal plains, as inferred by Wolff (1960). The combined findings of Glud et al., (2013) and Wenzhöfer et al., (2016) revealed elevated diagenetic activity in the trench axes of three contrasting trenches underpinning the importance of hadal ecosystems for the deep sea carbon cycling.

The salient point of all of this section is that there is a great deal to be gained by adopting a multi-depth and multi-trench approach; an issue that is discussed further later in section 7.

3. Scientific Literature

In recent years the research effort in hadal science has increased as reflected by an on-line search for peer-reviewed scientific papers on Thomson Reuters 'Web of Knowledge' journal search engine (http://wok.mimas.ac.uk/). Searching the term 'hadal', listed 191 papers between 1956 and 2017 (Fig. 1). Almost half of these papers were published in the last 10 years, and just over a quarter in the last 5 years. The maximum number of hadal papers published was equally in 2015 and 2017 (12), although 2018 is likely to achieve more as there are currently >10 'in press' at the time of writing. This increase is an encouraging trend in research output but it is still significantly lagging behind similar work from shallower depths ecosystems. For example, the same search using the term 'abyssal' produces 5135 papers, 'hydrothermal vent' produces 6811 papers, 'seamounts' produces 5305 papers, and 'continental shelf' produces 22,334 papers. These values were derived in September 2016. It is worth noting that the search does not necessarily capture a lot of publications published in Russian, nor does it include geological or geophysical papers relating to subduction zones.

The trends in publications also reflect, to some degree, changes in sampling effort and associated technology. For example, there was a steady output of material from 1956 to the mid-1990s following the *Galathea* and *Vityaz* expeditions, supplemented by several other studies. This was followed by a steep increase following the ROV *Kaiko* coming on line, which interestingly saw a drop in numbers of papers published in the early 2000s following its loss. This was followed by a resumed and rather stark increase as the uptake of lander based studies became common place.

4. Conferences and Symposia

One of the outcomes of the first HADEEP project (2006-2011; Jamieson et al., 2009c) was 'Trench Connection'; the first international symposium focussing entirely on the hadal zone biology, ecology, geology and technology (Jamieson and Fujii, 2011). It was held at the University of Tokyo's Atmosphere and Ocean Research Institute (AORI) in November 2010. The symposium attracted an international collective of 70 scientists and engineers from six countries, to discuss the latest developments in hadal science and exploration. The 2012 13th Deep-Sea Biology Symposium in Wellington, New Zealand was the first in this symposium series to include a session specifically dedicated to hadal biology. Likewise, in 2015 at the 14th Deep-Sea Biology Symposium in Aviero, Portugal, another half day hadal session was held. In 2016, the emerging interest of the Chinese in hadal science saw the 'First International Summit on Hadal Zone Exploration', dubbed 'Hadal Geek' held in Shanghai and saw nearly 300 participants in 2 days. In August 2017 there was a session entitled 'Exploring the Hadal Zone: Recent Advances in Hadal Science and technology" at the Goldschmidt 2017 conference in Paris, France. Combined, these events highlight the increasing effort and positive interest in hadal science.

5. Conservation

The legacy and reach of anthropogenic influence is perhaps most clearly demonstrated by its impact on the most remote and inaccessible habitats on Earth (Jamieson et al., 2017). The 1980s saw the first direct attempt to conserve the trenches from anthropogenic activities (Angel 1982). This was in response to talk of dumping nuclear waste and other unwanted material, which, with the exception of pharmaceutical dumping in the Puerto-Rico trench (Simpson et al., 1981), thankfully never took place. In January 2009 the Mariana Trench was officially declared 'a marine reserve' by former U.S. President George W. Bush who created the 95,216 square mile Mariana Trench Marine National

Monument (MTMNM, Presidential Proclamation 8335; Tosatto, 2009): the largest marine reserve under the authority of the Antiquities Act of 1906. The MTMNM envelopes submerged lands and waters of the Mariana Archipelago and extends from the northern limit of the Exclusive Economic Zone (EEZ) of the U.S. in the Commonwealth of the Northern Mariana Islands (CNMI) to the southern limit of the EEZ of the U.S. in the Territory of Guam. The monument boundary encompass nearly all of the Mariana Trench.

A similar initiative was announced in September 2015 to create the Kermadec Ocean Sanctuary about 1000 km off New Zealand. The 620,000 km^{-2} sanctuary that encompasses most of the Kermadec Trench, is to largely protect against anthropogenic activity that may harm seabirds, coastal and commercial fishing stocks. It does, however, also now protect the trench from the possibility of oil, gas and mineral prospecting, exploration and mining. The intention is to have the sanctuary in place by November 2016.

With the exception of a changing climate that will affect the entire ocean (Smith et al., 2006, Smith et al., 2008) adverse effects of anthropogenic activity such as the deliberate dumping of waste products in trenches is now unlikely to occur. Furthermore, other direct impacts such as industrial extraction of hydrocarbons or mineral resources from trenches is not likely to occur in the foreseeable future. However, issues regarding climate change do pose serious issues for hadal communities that are as intrinsically linked to surface-derived food supply as much as any deep-sea ecosystem. These changes will likely lead to alteration in the structure, function and biodiversity in the ecosystem (Smith *et al*., 2008; Bopp et al., 2013; Woolley et al., 2016). However, the critical issue for trench communities is that there are no long-term datasets on which to derive baseline knowledge or that could underpin management strategies in the future.

Anthropogenic pollution, contamination, and litter debris are globally worrying trends (Ramirez-Llodra et al., 2011). In the aftermath of the 2012 *DEEPSEA CHALLENGE* dive, Hartmann and Levin (2012) highlighted concerns that the deepest oceans are no longer beyond the reach of human activities. They reported on the finding of bovine DNA in the stomach contents of amphipods from the Tonga Trench (Blankenship and Levin 2007) which could arguably be explained by ship galley discards. There are also reports of finding a raincoat at *Challenger Deep* (Lee 2012) and other anecdotal observations such as the presence of a Canadian beer can at 6037 m in the Kermadec Trench (personal observation), and a wine bottle at ~8228 m in the New Britain Trench during the *DEEPSEA CHALLENGE* Expedition (personal communication – N. Gallo). Some of the deepest litter ever reported in the literature was at 7216 m in the Ryukyu Trench off Japan (reported in Ramirez-Llodra *et al.,* 2011) which has recently been shown to significantly accumulate litter debris towards the trench axes relative to the surrounding abyssal plains and continental shelf regions (Shimanaga and Yanagi 2016). This latter study went as far as declaring that trenches and troughs function as ‘depocenters’ for anthropogenic litter, following the same transport mechanism as food supply (Danovaro et al., 2003). Following on the same theme, Jamieson et al. (2017) reported extraordinary bioaccumulation of persistent organic pollutants (POPs) in hadal amphipods from both the Kermadec and Mariana trenches; namely polychlorinated biphenyls (PCB) and polybrominated diphenyl ethers (PBDE). Indeed, in the Mariana Trench, the highest level of PCBs were fifty times more contaminated than crabs from paddy fields fed by the Liaohe River, which is the most heavily polluted river in NE China (Teng et al., 2013). The high levels of contamination in these trenches, particularly the Mariana Trench may be a result of proximity to the highly industrialised regions in the NW Pacific (Felker 2001) and given it underlies the North Pacific Subtropical Gyre, dubbed the ‘Great Pacific Garbage Patch’ (Kaiser 2010) is susceptible to POP transport via plastic debris. Secondly, the amphipods may be accumulating POPs through scavenging on surface derived carrion-falls pre-contaminated from surface-water and atmospheric sources. But ultimately, the trench topography offers a funnelling mechanism of food and any adverse substances that comes with it into the ecosystem, but offers very little opportunities for dispersal.

Hartmann and Levin (2012) highlighted the importance of considering conserving these ‘pristine’ environments, even whilst undertaking scientific endeavours. An ever increasing use of scientific instrumentation could result in an accumulation jettisoned ballast weights, accidental losses of vehicles in whole or in part, and focal points such as *Challenger Deep* could potentially become analogous with the human-derived debris currently residing at very high altitudes on Mount Everest (Panzeri et al., 2013).

6. Biodiscovery

The marine environment is currently emerging as a hotbed of microbial diversity that has rarely been exploited for biotechnological gain (so-called ‘blue biotechnology’; DeSilva, 2004), despite preliminary work showing huge potential (Fang and Kato, 2010). Extremophiles from extreme deep-sea habitats such as the hadal trenches, as well as the Polar Regions, O_2 minimum zones and chemosynthetic habitats are also likely repositories of potentially novel biocompounds (Rittman and McCarty, 2001; Harden-Davies, 2017). The properties and potential applications of these compounds have rarely been fully appreciated (Allen and Jaspars, 2009). Research on marine natural products (MNPs) is now evolving into a multidisciplinary international venture under the umbrella terminology of ‘bioprospecting’ or perhaps more appropriately, ‘Biodiscovery’.

Possible biotechnology applications for deep-sea ‘piezophiles’ (pressure-loving) have proven slow to develop as a result of difficulties in cultivation at great hydrostatic pressures. The number of reported compounds currently isolated from hadal organisms is <10 (Arnison et al., 2013), and recently, 12 more compounds have been isolated from a pressure-tolerant bacterium found in Mariana Trench sediment (Abdel-Magreed et al., 2010). Recent evidence shows that piezotolerant bacteria from Mariana Trench sediments produce biologically active and unusual secondary metabolites with great potential (M. Jaspars, unpublished, University of Aberdeen, UK). Further exploration, discrete sampling and cultivation of trench material will likely yield microorganisms from clades that are far removed from those found in other environments, thus increasing the possibility of discovering new chemical entities with potent and selective bioactivity.

7. The ‘Challenger Deep’ effect

In terms of providing a contemporary perspective on hadal science, there is an emerging issue of a Mariana Trench problem: the Mariana Trench, or rather specifically, the *Challenger Deep*, represents *the* place to go in many new trench initiatives. Historically JAMSTEC spent a great deal of ROV *Kaiko* time in the *Challenger Deep*, albeit later moved to other NW Pacific trenches, but the publicity surrounding the *DEEPSEA CHALLENGER* dive and now the emergence of China as ‘hadal explorers’ there is an ever increasing focus on technology to explore *Challenger Deep*, as highlighted by the ‘Haidou-1’ deployments in 2016 when the Chinese Academy of Sciences announced in the media this vehicle had successfully dove to 10,767 m. Likewise, the tests of the larger exploratory vehicles of the Hadal Science and Technology Center at Shanghai Ocean University are due to be performed at the *Challenger Deep*, and *Challenger Deep* has been the focus of many discussions at the afore mentioned conferences and symposia as the ultimate ‘goal’ in hadal exploration. However, *Challenger Deep* poses a number of concerns as the driving location for future scientific endeavour. These concerns are largely because the Mariana trench is somewhat of an outlier among trenches. The trench underlies one of the most oligotrophic surface waters, it is one of the most remote from continental land masses, and thus terrestrial organic matter input (Gallo et al.,2015), and of course it stands out there as the deepest (albeit not by much). Furthermore, it is only one trench, and only one of 5 of 37 trenches that exceed 10,000 m (Jamieson 2015). That alone makes it difficult to resolve how it might represent the ‘hadal zone’ on its own. The issues are exacerbated further as trench topography is such that the area of seafloor exponentially diminished with depth resulting in less than 1% of any 10,000 m deep trench being greater that 10,000 m (Jamieson 2015), thus the minute percentage of it that constitutes the *Challenger Deep* is even more of an outlier in terms of how much it represents the hadal ecosystem. Given the extreme depth, ultra-low energy input and reduced focal point of study, the *Challenger Deep* does not readily offer a representative location in which to underpin new theory in hadal science, it should really represent one of many points of study for wider context. Ironically, the focus on *Challenger Deep* did in fact result in the rest of the entire Mariana Trench going largely unstudied until the 2014 'HADES-M' cruise on the RV *Falkor* (e.g. Linley et al., 2016), and paradoxically, *Challenger Deep* is now actually the most well-known and explored area in the hadal zone. There are, however, other trenches that exceed 10,000 m in more energy rich waters, particularly the Kurile-Kamchatka Trench, and medium trophic level trenches such as the Philippine, Kermadec and Tonga Trenches that would perhaps be more representative in the 'hadal' context. However, picking any one trench that most represents all trenches is difficult: Some are relatively eutrophic (Japan Trench), some sub-zero (South Sandwich Trench), some receive considerable plant and wood debris (Puerto Rico and New Britain trenches), some span great latitudinal gradients (Peru-Chile Trench) while others can span great longitudinal gradients (Aleutian Trench).

If hadal science is progress effectively, it must at the very least try to systematically sample the entire depth range of any trench (not just the *Deeps*), and preferably as many trenches as possible. This should also include down both plates, as the underriding plates are often more benign and sedimented than the steeper, topographically more complex overriding plates. To inject some perspective here through analogy, scientists studying hydrothermal vents would not focus solely on the hottest vent and ignore the rest, nor would seamount researchers exclusively study the biggest 'pointiest' seamount and nothing else, in fact the best analogy to put the Mariana Trench problem in context is the question: how much would we learn about the world's mountain flora and fauna by only ever studying the summit of Mount Everest?. Not very much? So why is hadal science suffering from this 'Challenger Deep' effect? The answer appears to be the hottest vents and biggest seamounts do not offer the same sense of 'frontier' as depth does. Explorers do not set out to find the *biggest* submarine canyons or the *most* chemically rich cold seep, or the *most* saline brine pool, but human nature is such that they are drawn instinctively towards the *deepest* place on Earth, which throws it at odds with sound scientific endeavour. Couple this with the engineering challenges of access and the need for proof of accomplishment, the Mariana Trench and its deepest point present a somewhat frustrating grey area between sound scientific endeavour and adventure that must be carefully interpreted.

This problem also provides some truth in the fears discussed by Hartmann and Levin (2012) who warned against increasing activity in such an acute area where the discarding of even just small objects, but frequently, may result in the same difficult scenes at the deepest point on Earth as we see at the highest altitude on Earth.

8. Conclusions

The challenges for the immediate future are two-fold. Firstly, there is a technology and access challenge. The challenge being to develop low cost, compact and innovative methods by which to access the greatest depths in order to perform multidisciplinary observational and experimental tasks, including chronically-overdue long-term monitoring (Jamieson and Fujii, 2010). This comes at a time where the reliance on large deep-submergence platforms, such as ROVs, HOVs and AUVs, may dwindle due to financial strain on engineers and designers to develop tools for full ocean depth that have been previously restricted to shallower waters (Monastersky, 2012).

The second is to challenge the perception of the scientific community to ensure the hadal communities are included in future research programmes alongside other marine environments to encourage a more holistic approach to marine science, especially given the climate-related changes and the predicated cascading effects on the underlying habitats (Smith et al., 2008; Levin and Le Bris, 2016). Furthermore, depth related trends in diversity, biology, physiology and ecology, among many others, are likely to be heavily influenced by the incorporation of the deepest 45% of the ocean and its fauna.

Meeting these challenges must involve sampling of multiple trenches with sufficient resolution, bathymetric coverage and replication to enable globally relevant ecological theory and resist the temptation to relate everything to depth alone. There are popular statements that underpin the perspective that the hadal trenches are remote and inaccessible, such as analogies like “if Mount Everest was placed into the Mariana Trench its summit remains a mile below the surface”. However, Jamieson et al. (2017) highlighted that the distance from the surface to *Challenger Deep* is actually only equal to half the length of Manhattan Island, emphasizing that human proximity to these ‘extreme’ environments is far from remote and can explain why they are no longer pristine. These sentiments must then run parallel to others such as that of Hartmann and Levin (2012) in avoiding creating a science-induced dumping ground in *Challenger Deep*, yet responsibly exploiting the potential for biodiscovery (Rittman and McCarty, 2001; Harden-Davies, 2017), while producing large statistically robust datasets that could potentially underpin management initiates and serve, for the first time, something resembling baseline data.

Woven through all of the above we must remember that the characteristic extreme environmental pressures require important non-trivial evolutionary adaptations for survival that provides incredible opportunities for the next generation of natural historians in whatever guise they take (but avoiding the lure of the “*Challenger Deep”* effect). Furthermore, these pursuits presents a major and utterly fascinating technology and engineering challenge that will underpin it all. We now live in an age where technological progress means that few truly unexplored frontiers remain, the hadal zone is testament to just that, it is now simply a game of ‘catch-up’.

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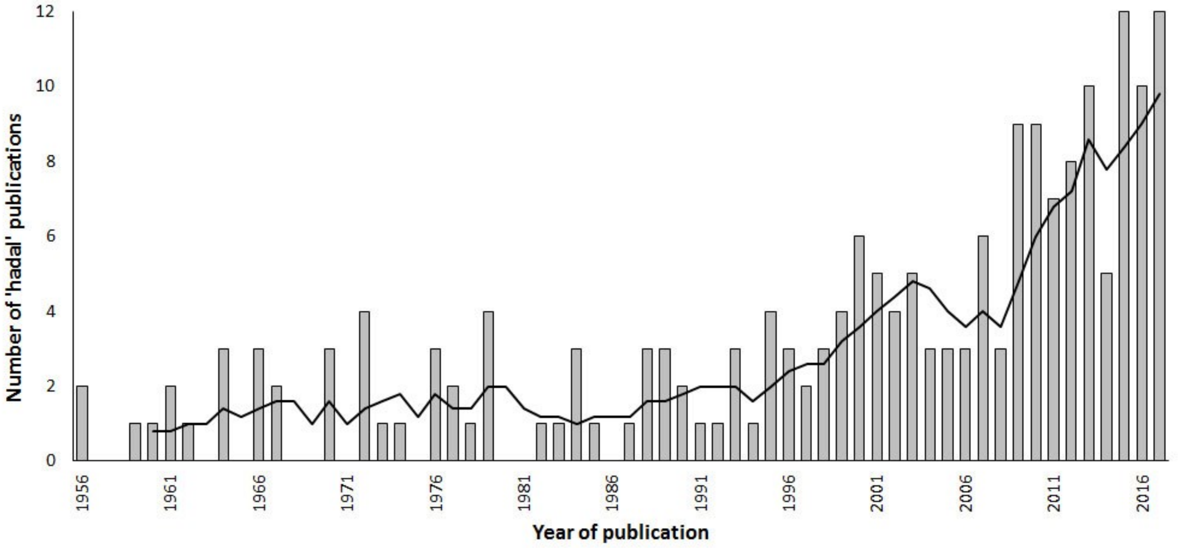

Figure 1. The number of peer-reviewed scientific papers containing the keyword ‘hadal’ per year since 1956 (Grey bars). The trend line represents a moving 5-year average (Updated from Jamieson 2015).