INTRODUCTION

In a seminal paper submitted to the first meeting of the Subsidiary Body on Scientific Technical and Technological Advice of the 1992 *Convention on Biological Diversity,*[1] Glowka suggested that, given a comprehensive legal regime already exists for the mineral resources of the deep-sea beyond national jurisdiction, an "intriguing question" needs to be addressed as to whether a legal and institutional regime should be created for the genetic resources of the deep-sea beyond national jurisdiction.[2] Glowka's paper highlighted a major lacuna in international law. Part XI of the 1982 United Nations Convention on the Law of the Sea[3] and the euphemistically labelled 1994 Implementation Agreement in relation to Part XI of LOSC[4] established a very detailed international regime governing exploitation and benefit sharing in relation to the mineral resources of the deep-sea beyond national jurisdiction, known under LOSC as the Area. However, mining in the Area appears to be many years away. Instead the genetic resources of the deep-sea appear to be the most immediately exploitable resource of the deep-sea apart from fisheries. Access to such resources on

[1] United Nations Convention on Biological Diversity, opened for signature 5 June 1992, 31 ILM (1992) (entered into force 29 December 1993), herein referred to as the CBD.
[2] Glowka's submission to SBSTTA was published as Lyle Glowka, 'The Deepest of Ironies: Genetic Resources, Marine Scientific Research, and the Area' (1996) 12 *Ocean Yearbook* 154.
[3] United Nations Convention on the Law of the Sea, opened for signature 10 December 1982, 21 ILM 1245 (1982) (entered into force 16 November 1994), hereinafter LOSC.
[4] Agreement relating to the Implementation of Part XI of the United Nations Convention on the Law of the Sea of 10 December 1982, opened for signature 28 July 1994, 33 ILM 1309 (entered into force 28 July 1996), hereinafter Part XI Agreement.

the high seas is unregulated as neither LOSC and the Part XI Agreement nor the CBD currently have meaningful application to these newly exploited resources.[5]

This thesis provides a response to Glowka's "intriguing question" and some associated issues. However, rather than viewing this issue primarily as a question pertaining solely to the fair and equitable utilization of the Area's genetic resources, this thesis addresses a much broader issue: that is how can all human activities that have an environmental impact on deep-sea hydrothermal vent ecosystems be sustainably managed, so that this particularly unique ecosystem of international significance is preserved for future generations? The issue of the fair and equitable utilization of the Area's genetic resources is but one subsidiary issue that needs to be addressed in responding to this overall question.

This thesis only considers the sustainable management of deep-sea hydrothermal vent ecosystems and not all ecosystems in the deep-sea that are also subject to bioprospecting. Increasingly the deep-sea, and beyond it the deep biosphere,[6] are of interest to both science and industry. In addition to hydrothermal vents a range of biological communities and habitats in the deep-sea including deep-sea sediments,

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5 Above, n 2.

6 Living bacteria and archaea are believed to exist hundreds of metres below the sea-bed and probably to depths where thermogenic geosphere processes occur. Several research institutions are currently exploring the deep biosphere. For example see the European Union funded research project 'DeepBug' http://www.chm.bris.ac.uk/deepbug/index.htm accessed 1 July 2004, the Deep biosphere work of the Ocean Drilling Program http://www.odp.tamu.edu/publications/185_IR/chap_01/c1_11.htm accessed 1 July 2004, or the Research Program for Deep-subsurface extremophiles at JAMSTEC http://www.jamstec.go.jp/jamstec-e/bio/en/mesubex.html accessed 1 July 2004. See also Y Tanaka et al 'Evidence of sub-vent biosphere: enzymatic activities in 308°C deep-sea hydrothermal systems at

methane seeps, and even the deepest points in the ocean such as the Mariana Trench (a depth of some 11,035 metres)[7] have all been sampled with an eye to their biotechnology potential. The "intriguing question" posed by Glowka applies equally to these and other components of the deep-sea ecosystem(s). However, from the very early stages of this research it was decided to limit consideration to the sustainable management of deep-sea hydrothermal vents and their associated biological communities. This was for a number of reasons. Firstly, as Chapter 1 outlines, this ecosystem is of particular importance in terms of the overall biodiversity of the deep-sea. Similarly, although other components of the deep-sea ecosystem are of interest for biotechnology, for the time being the major focus is on microbial life forms from deep-sea hydrothermal vents. More importantly given the range of issues raised by hydrothermal vents alone, it would be difficult to undertake the detailed analysis which is justified in relation to the entire deep-sea ecosystem in just one PhD thesis.

Accordingly research was confined to deep-sea hydrothermal vents, notwithstanding many of the issues discussed are of equal importance in relation to other components of the deep-sea ecosystem. Having limited this research to hydrothermal vents however, many of the issues raised and the conclusions reached arguably are applicable to other components of the deep-sea ecosystem. Perhaps later research

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Suiyo Seamount, Izu-Bonin Arc, Western Pacific Ocean' (2005) 229 *Earth and Planetary Science Letters* 193.

[7] In March 1996 JAMSTEC successfully sampled some 3000 microbial strains from the Mariana Trench which are now stored for future research by their Bioventure Center for Extremophiles. See http://www.jamstec.go.jp/jamstec-e/bio/seaex/mariana.html, accessed 1 July 2004.

could canvass similar issues in relation to other deep-sea habitats such as methane seeps, deep-sea sediments and the deep biosphere.

Similarly, although measures to conserve hydrothermal vents raise issues associated with MPAs on the high seas and this thesis does contain some discussion of this subsidiary issue, consideration of mechanisms to establish high seas MPAs have been excluded from this research. This is largely due to the fact that the issue of high seas MPAs of themselves could fill an entire PhD thesis. The writer is aware of at least two other PhD students in Australia who are currently working on PhD theses in relation to high seas MPAs.

The thesis commences in Chapter 1 with consideration of the nature and importance of the hydrothermal vent ecosystem. Simply put it seeks to address one fundamental question: why should we bother about the sustainable management of this particular deep-sea ecosystem? The answer provides the philosophical framework which governs subsequent analysis in this thesis.

Chapter 2 then examines the existing status of hydrothermal vents and their associated biological communities under international law. Precisely what is the lacuna in the law that has been suggested? Since Glowka's original analysis there have been a number of developments on this issue and these are also surveyed in Chapter 2. This includes consideration of developments up until December 2004. Discussion in this chapter includes a brief review of core principles and concepts of international environmental law of relevance to considering hydrothermal vents, an overview of the relevant provisions of LOSC and the Part XI Agreement, as well as developments at the United Nations Informal Consultative Process on the Law of the Sea[8] and within the institutions associated with the CBD. Detailed consideration of a number of relevant developments within the institutions of the International Seabed Authority[9] is deferred until Chapter 9.

Chapter 3 considers the potential application of regional and other treaties that have so far received little attention in the literature. This chapter examines the extent to which existing regional and other treaties apply to deep-sea hydrothermal vents. Could any of these regional or other treaties provide mechanisms that could be used to provide for the sustainable management of hydrothermal vent sites?

One issue of significance that has been touched on briefly in the existing literature is the extent to which the Continental Shelf Regime under Part VI of LOSC applies to hydrothermal vent sites on the continental shelf. The general nature of this issue is introduced in Chapter 2. A historical analysis of the origins of the Continental Shelf Regime is undertaken in Chapter 4 and examines why problems associated with the application of the Continental Shelf Regime to the hydrothermal vent ecosystem have arisen. Chapter 6 illustrates the difficulties the Continental Shelf Regime may pose for New Zealand.

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[8] Herinafter UNICPLOS.

Chapter 5 considers the extent to which the concept of the Common Heritage of Mankind is relevant to the design of a legal regime for the sustainable management of deep-sea hydrothermal vents in areas beyond national jurisdiction.

Chapter 6 then goes on to examine emerging legal regimes associated with hydrothermal vents located within areas of national jurisdiction. Specifically, the chapter addresses recent developments in Canada, New Zealand, Portugal and PNG. The domestic legal regimes for the management of hydrothermal vent sites are examined for a number of reasons. Firstly, to date there has been little examination of the sustainable management of hydrothermal vents and other deep-sea ecosystems in the legal and policy literature.[10] Examination of these four regimes therefore adds to the literature in relation to measures to sustainably manage deep-sea ecosystems within national jurisdiction. More importantly, examination of these domestic legal regimes may provide some guidance as to what factors may need to be considered when designing an international legal regime for the sustainable management of hydrothermal vent sites beyond national jurisdiction.

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[9] Hereinafter ISA.

[10] During the course of this research parts of Chapter 6 were published as D K Leary, 'Law Reaches New Depths: The Endeavour Hydrothermal Vents Marine Protected Area' In J P Beumer, A Grant and D C Smith (Eds), *Aquatic Protected Areas. What works best and how do we know? Proceedings of the World Congress on Aquatic Protected Areas* (2002), 85-96.; D Leary, 'Emerging Legal Regimes regulating bioprospecting for thermophiles and hyperthermophiles of hydrothermal vents', (2004) 6 *Marine Biotechnology*, S351 and D K Leary, 'Bioprospecting and the genetic resources of hydrothermal vents on the high seas: what is the existing legal position, where are we heading and what are our options?' (2004) 1(2) *Macquarie Journal of International and Comparative Environmental Law* 137. A later publication by Glowka covers some of the same ground. See L Glowka, 'Putting marine scientific research on a sustainable footing at hydrothermal vents' (2003) 27 *Marine Policy* 303.

Chapter 7 addresses issues associated with bioprospecting at hydrothermal vents in areas beyond national jurisdiction. This chapter addresses key threshold issues such as the nature and extent of bioprospecting at hydrothermal vents. Is there in fact any commercial interest in bioprospecting? If there is, what factors need to be considered when designing a legal regime for fair and equitable sharing of benefits that may arise from such bioprospecting?

Chapter 8 then goes on to examine MSR and, in particular, how its environmental impact may be sustainably managed. This chapter is based in part on interviews conducted with scientists engaged in research in relation to hydrothermal vents in Australia, New Zealand, Canada, Portugal, Japan and PNG. It considers the nature of MSR, whether MSR should be subject to regulation, and what form that regulation should take.

Chapter 9 examines the question of mining at deep-sea hydrothermal vents and examines the future role of the ISA in relation to the sustainable management of hydrothermal vents beyond national jurisidiction. This includes a critical analysis of the existing mandate of the ISA and considers how it has fulfilled that mandate since its establishment with the entry into force of Part XI of LOSC and the Part XI Agreement. This chapter seeks to address the question as to whether the ISA should be entrusted with an expanded mandate to sustainably manage activities in addition to mining.

Chapter 10 draws together conclusions reached in preceding chapters and outlines conclusions as to how deep-sea hydrothermal vents beyond national jurisdiction could be sustainably managed.

Much of the material in this thesis is interdisciplinary. The inclusion of a range of non legal material in this thesis is justified on a number of grounds. Firstly, there has been little examination of these issues in legal and policy literature. There has been some consideration in the scientific literature and hence it was useful to draw on that literature. Secondly, in order to understand the legal issues canvassed in this thesis, it is also necessary to understand some of the commercial and scientific issues at stake. In many respects this thesis is not just a thesis in relation to a legal problem but also canvasses issues that have an impact on science and on commerce. As Borgese has argued, in approaching any new problem associated with the Law of the Sea one basic and simple principle should always apply, that is:

> "If the issues under consideration are interdisciplinary, the decision-making process must be interdisciplinary"[11]

Hence analysis in this thesis draws on a range of interdisciplinary literature and the views of many non-lawyers.

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[11] E M Borgese, 'The Process of Creating an International Ocean Regime to Protect the Ocean's Resources', In J M Van Dyke et al (eds) *Freedom for the Seas in the 21st Century: Ocean Governance and Environmental Harmony* (1993), 29.

CHAPTER 1

INTRODUCTION-SHIFTING PERCEPTIONS AND SHIFTING THE CONSERVATION AGENDA TO THE DEEP-SEA.

" I don't know why I don't care about the bottom of the ocean but I don't"[1]

For many thousands of years, and until quite recently, humanity's attitude to the deep-sea was shaped largely by myth fuelled by ignorance. Across recorded history, across all cultures and continents, humanity has traditionally characterised the deep-sea as an evil, foreboding place.[2] Throughout time one word has been used to describe the deep-sea more than any other. That word, "resonating with sinister energy", is the "abyss".[3] The deep-sea has been labelled the abyss, from the Greek words *a*, without, and *byssos*, bottom – a synonym for dark infinities and primal chaos.[4] It was unknown and unknowable, unconnected to anything remotely human.[5] As Broad notes:

> "It was cold. It was dark. Worst of all, it was well known to harbor [sic] the most loathsome aspects of creation, some of which from time to time crept upward from the unilluminated depths to bedevil man [sic]".[6]

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[1] Text from a famous Cartoon about the deep-sea reproduced in Cindy Lee Van Dover, *The Octopus's Garden: Hydrothermal Vents and other mysteries of the Deep Sea* (1996), 161.
[2] J B Sweeney, *A pictorial history of sea monsters and other dangerous marine life*, (1972).
[3] W J Broad, *The Universe Below: Discovering the Secrets of the Deep Sea,* (1997), 21.
[4] Broad, above n 3, 21-22.
[5] Broad, above n 3, 21.
[6] Broad, above n 3, 22.

Very few people except for a handful of very privileged scientists and an even smaller number of tourists and journalists[7] have ever experienced the deep-sea first hand, or come close to any of the species that occupy its hidden realm. Until quite recently we did not know what was at the bottom of the oceans. Nor did we know what the bottom of the ocean was made of.[8] In most areas, we did not even know where the bottom of the ocean actually was.[9]

Given our ignorance and the characterisation of the deep-sea as a cold, dark, forbidding place, it is not surprising that the deep-sea has not figured prominently on the conservation agenda. To date we have simply not understood or cared much about the deep-sea. Therefore there have been very few legislative measures implemented for deep-sea conservation either at the domestic or international levels. Where there has been interest in deep-sea conservation it has largely been species-orientated.[10] Whaling, whale sanctuaries and straddling and highly migratory fish stocks being several examples.[11] Few deep-sea ecosystems have received formal protection through designation as MPAs. Those areas of the deep-sea that have received some level of protection, such as seamounts, have only been protected because of their close association with fish stocks exploited for food.

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[7] One of the privileged few journalists is William Broad who has written a fantastic account of his experiences as a deep-sea journalist. Broad, above n3.
[8] R Ellis, *Deep Atlantic: Life, Death, and Exploration in the Abyss*, (1996), 4.
[9] Ellis, above n 8.
[10] P K Probert, 'Seamounts, sanctuaries and sustainability: moving towards deep-sea conservation.' (1999) 9 *Aquatic Conservation: Marine and Freshwater Ecosystems* 601, 603.
[11] Probert, above n 10.

While it is a cold and dark place, contrary to popular myth, the deep-sea is a truly beautiful and amazing place. There are no sea monsters, just an amazing diversity of ingenious and adaptive life. In terms of biodiversity it is perhaps the most species rich habitat on the planet. It is the largest area of the planet that supports complex life, constituting somewhere between 78.5% and 97% of the global biosphere.[12] As such the deep-sea constitutes the most typical environment, and its inhabitants the typical life forms of planet earth.[13]

Increasingly the deep-sea is under threat from human activity. As a consequence there is now an urgent need to shift the focus of the marine conservation debate from the coastal and shallow waters to the high seas and the deep-sea in particular. If we are serious about the conservation of biodiversity of our planet (which the writer optimistically believes we are) then our focus must shift to include a greater focus on the most typical habitat on planet earth, that is the deep-sea. Moving the conservation debate to encompass conservation of vulnerable deep-sea habitats is arguably the most important challenge of the next few decades.[14]

This thesis focuses on one particular component of the biodiversity of the deep-sea, that associated with hydrothermal vents or deep-sea submarine volcanic springs. Even though science is only really just beginning to comprehend the complexity and

[12] W J Broad, above n 3, 45.
[13] J D Gage and P A Tyler *Deep-Sea Biology: A natural history of organisms at the deep-sea floor,*(1991), xi.

[14] Probert, above n 10.

diversity of life in the deep-sea, scientific evidence suggests that a significant component of the diversity of life in the deep-sea is to be found at hydrothermal vents. Their discovery in 1977 has rightly been labelled one of the most significant developments in Oceanography of the 20th Century.[15] However, just as we are slowly beginning to comprehend how important hydrothermal vents are in terms of the overall biodiversity of the deep-sea, even at these great depths this amazing diversity of life is under threat from human activity.

OVERVIEW OF CHAPTER

This chapter introduces key components of the deep-sea environment and the biodiversity of the deep-sea with a particular focus on the ecosystems associated with hydrothermal vents. Although all ecosystems are in part a product of their local geology and other environmental conditions, as the first part of this chapter outlines, the hydrothermal vent ecosystem is closely dependant on the underlying geological processes associated with plate tectonics. This is because, through chemosynthesis, the underlying geological processes quite literally provide the food upon which the ecosystem feeds and thrives.

The second part of this chapter then goes on to consider the nature of the biodiversity of the deep-sea generally and the unique features of hydrothermal vents within the context of the overall biodiversity of the deep-sea. This section introduces the key biological features of hydrothermal vent ecosystem. In later chapters, where specific

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[15] P Dando and S K Juniper, *Management and Conservation of Hydrothermal Vent Ecosystems*, Report from an InterRidge Workshop, Institute of Ocean Sciences, Sidney (Victoria), B.C. Canada 28-30 September, 2000, (2001), 2.

sites are examined, such as those associated with MPAs, more details are provided on the biology and ecology of those specific sites.

The final part of this chapter then presents several reasons why we should be concerned about the environmental impact of human activities on hydrothermal vent ecosystems. Why should we bother?

This Chapter therefore seeks to lay the foundation for an understanding of the unique ecosystems of hydrothermal vents and their place in our emerging understanding of the biodiversity of the deep-sea; one very large component of global biodiversity, which is only vaguely understood by science and to date almost totally ignored by lawyers. It is hoped that with a shift in perception, there will also arise an understanding of the need for action. How that can be achieved will then be the focus of later chapters of this thesis.

The relationship between plate tectonics, the formation of the mid-oceanic ridge system and hydrothermal vents

The earth's outer shell consists of a mosaic or patchwork of broad, rigid lithospheric plates. These plates lie on top of a partially molten, plastic asthenosphere that facilitates their movement.[16] Although the lithospheric plates behave as rigid bodies, the boundaries of adjacent plates are dynamic and interact in three main ways: firstly, by diverging or spreading, as at mid-oceanic ridges; secondly, by converging at deep-

[16] M J Kennish, *Practical Handbook of Marine Science* (2001), 279

sea trenches; thirdly, at some plate boundaries transform faults slip sideways past each other.[17]

New lithosphere is created at the mid-ocean ridges. The 75 000 kilometre long mid-oceanic ridge system arises from volcanic eruptions at diverging plate boundaries in the deep-sea. [18] The mid-oceanic ridges typically lie at depths of between 2000 and 3000 metres. They are the largest and most volcanically active chain of mountains on Earth, extending around the planet.[19]

The volcanic ridges are highest along the ridge crests, and, as newly formed lithosphere cools, subsides, and accelerates away from the ridge axis, the rugged terrain gradually tapers away to the smooth surface of the abyssal hills covered with sediment. [20] This lithosphere is reabsorbed or destroyed at convergent plate boundaries, namely the subduction zones marked by deep-sea trenches. At these destructive plate margins, one lithospheric plate overrides another, with the subducted (overridden) plate sinking into the mantle.[21]

Hydrothermal vents are formed due to the close proximity of heat-laden magma chambers to the seafloor, in conjunction with tectonic plate movement, which causes the convective circulation of dense, cold seawater through the cracked and fissured

[17] Ibid
[18] Kennish, above n 16, 280.
[19] Kennish, above n 16, 279
[20] Kennish, above n 16, 280.
[21] Kennish, above n 16, 279.

upper portions of the lithosphere.[22] Sea water penetrates down to the magma chamber and heats up.[23] The sea water is believed to penetrate to between 1.6 and 2.4 kilometres below the sea floor.[24] Heat transfers from the magma to the water.[25] As the fluid circulates within the crust it interacts with basaltic rock at high temperatures.[26] This causes clay and sulfate minerals to precipitate from the seawater resulting in a modified fluid with little to no magnesium or sulphate. As temperatures increase metals, silica and sulfide are leached from the rock, resulting in a hot, acidic fluid rich in silica, hydrogen, sulfide and metals, relative to seawater.[27]

Due to intense pressure on the deep ocean floor the temperature of the fluid can be as high as 350°C without boiling. At such an extreme temperature the water is very buoyant and when it finds a path through the sea floor it rises rapidly to the surface of the sea floor.[28] As the fluid exits, it passes from the sea floor to the surrounding seawater at high velocity. The mixing of the fluid with the surrounding seawater causes changes in pH and temperature and the precipitation of minerals.[29] Sulphide minerals crystallise onto the volcanic rocks forming a columnar chimney-like structure on the fissure.[30] At the same time fine grained sulphide and oxide minerals[31]

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[22] R A Lutz and M J Kennish, 'Ecology of Deep-Sea Hydrothermal Vent Communties.' (1993) 6(2) *Earth in Space* 11, 12.
[23] P Ré, 'Deep-Sea Hydrothermal Vents "Oasis of the Abyss"', In J Beurier A Kiss and S Mahmoudi (eds) *New Technologies and the Law of the Marine Environment,* (2000), 69.
[24] S E Humphris et al (eds), *Seafloor Hydrothermal Systems: Physical, Chemical, Biological, and Geological Interactions, (1995),* 87.
[25] M K Tivey, 'Hydrothermal Vent Systems.' (1991) 34(4) *Oceanus* 68, 69.
[26] Ibid.
[27] Ibid.
[28] Ibid.
[29] Ibid.
[30] Ré, above n 23.
[31] Tivey, above n 25, 70.

precipitate from the resulting solution appearing as black smoke.[32] Hence these columnar chimney structures are often called "black smokers".[33] This process is illustrated in Figure 1 below.

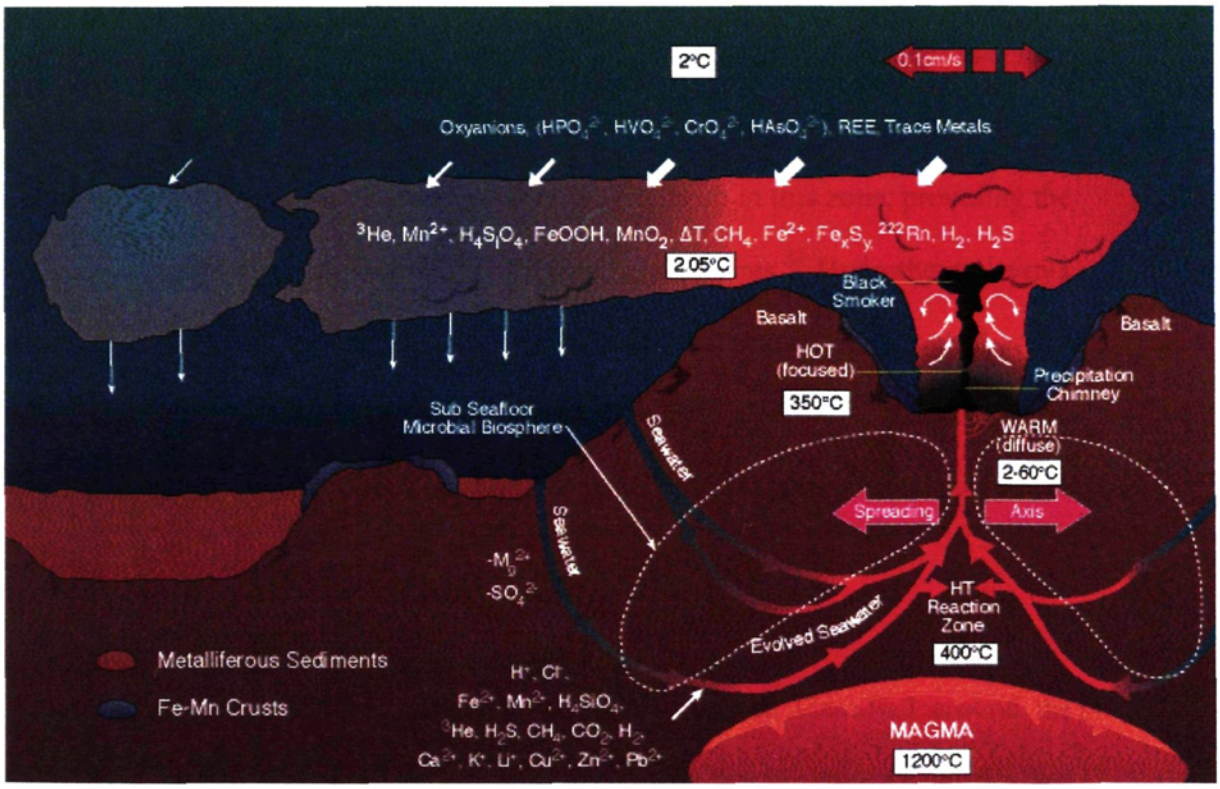

Figure 1: Illustration of how hydrothermal vents are typically formed.[34]

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[32] Ré, above n 23, 69.

[33] Although columnar chimney black smoker forms are common, not all hydrothermal vents fit this description. Apart from black smokers, complex sulphide mounds are perhaps the most impressive form of hydrothermal vent structure. These are typically huge structures, often towering metres above the adjacent ridge access. Examples include several located at the Endeavour hydrothermal vent field on the Juan de Fuca Ridge. These are freestanding sulphide mounds 10-30 metres in diameter and up to 40 metres or more in height. One such mound, known as 'Godzilla' because of its height, until it collapsed towered some 45 metres above the ocean floor. These huge structures also typically have multiple black smoker chimneys projecting from them. There are several other variations in morphology and mineral composition, including white smokers, beehives, flanges and massive sulphide deposits. Massive in terms of geology means material made up entirely of sulphide minerals. The term massive does not refer to the size or volume of such a deposit. As such a very small black smoker chimney can be a massive sulphide deposit. For further detailed discussion of the variations in morphology of hydrothermal vents see C L Van Dover, *The Ecology of Deep-Sea Hydrothermal Vents* (2000).

[34] Source: NOAA Web site: http://www.pmel.noaa.gov/vents/chemocean.html accessed 5 December 2002.

Hydrothermal vents generally form at mid-oceanic ridges, however some sites have also been identified at back-arc and fore-arc spreading centres. Back-arc spreading centres form behind island arcs where old lithosphere is subducted beneath a continental plate moving in the same direction.[35] The sinking slab [sic] of lithosphere pulls on the edge of the overlying plate, splitting it open and forming a zone of extension.[36] If sufficient heat is generated magma wells up in this zone, providing the heat source required for the formation of hydrothermal vents.[37] Hydrothermal vents have also been found associated with seamounts. This occurs whereever there is sufficient heat and porosity to drive hydrothermal convection.[38] Similarly, on occasion they have been found in the centre of plates where there are active submarine volcanoes.

Location of hydrothermal vent ecosystems

To date more than 100 hydrothermal vent sites have been identified around the world.[39] The most studied sites are located in the eastern Pacific (principally the East Pacific Rise and the Juan de Fuca, Gorda, and Explorer Ridges) and the north-central Atlantic (principally the Mid-Atlantic Ridge).[40] More recently sites have been discovered at twelve sites located on the Gakkel Ridge (which runs under the Arctic

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[35] Van Dover, above n 33, 36.
[36] Van Dover, above n 33, 36.
[37] Van Dover, above n 33.
[38] Van Dover, above n 33, 37.
[39] Ré, above n 33, 68.
[40] Van Dover, above n 33, 26.

Ocean from north of Greenland to Siberia) [41] and at least 13 sites identified within northern waters of New Zealand's EEZ.[42] Figure 2 below shows some of the main sites identified to date.

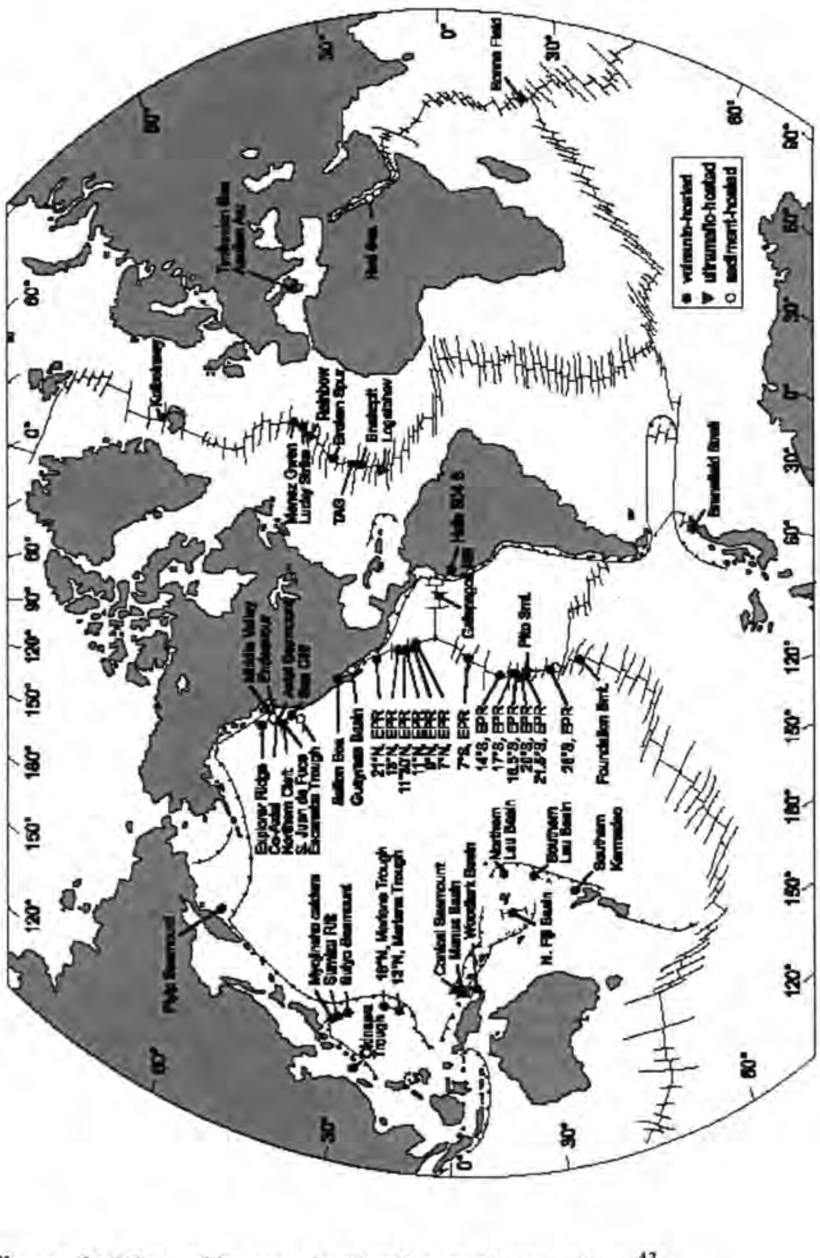

Figure 2: Map of known hydrothermal vent sites.[43]

[41] Reuters, 'Life, but not as we know it, on the boiling bed of a frozen ocean', *Sydney Morning Herald*. Sydney, 30 November, 2001.
[42] http://www.gns.cri.nz/news/release/hotsprings.html accessed 2 July 2002.

Given that the mid-ocean ridges are known to circle the globe for some 75 000 kilometres, it is probably reasonable to speculate that many more, possibly thousands, of hydrothermal vent sites lie hidden below the deep-sea, yet to be discovered. For example, little work has been done in the Southern Ocean close to Antarctica.[44] Given the size of the ridge system associated with the Antarctic and Australian Plates, it is probably reasonable to speculate significant hydrothermal vent sites lie on or adjacent to the boundaries of these plates.

Size and age of hydrothermal fields.

As noted above, the formation of the various types of hydrothermal vent structures is intimately linked to the underlying geological processes. Similarly, their frequency and size are very much dependant on the underlying geological processes. Individual vent fields[45] range in size from several hundred to several million square metres.[46] Some, such as the Venture Hydrothermal field on the East Pacific Rise, are scattered in a linear fashion along the walls of the narrow axial valley or eruptive fissure.[47]

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[43] Adapted from P M Herzig, S Petersen and M D Hannington, 'Polymetallic Massive Sulphide Deposits at the Modern Seafloor and their resource potential', In International Seabed Authority, *Polymetalic Massive Sulphides and Cobalt-Rich Ferromanganese Crusts: Status and Prospects. ISA Technical Study: No. 2.* (2002), 10

[44] Since commencing research for this thesis several possible hydrothermal vent sites have been identified in Antarctica. See L Somoza et al, 'Evidence for hydrothermal venting and sediment volcanism discharged after recent short-lived volcanic eruptions at Deception Island, Bransfield Strait, Antarctica' (2004) 203 *Marine Geology* 119 and G P Linkhammer et al, 'Discovery of new hydrothermal vent sites in Bransfield Strait, Antarctica' (2001) 193 *Earth and Planetary Science Letters* 395.

[45] The expression "vent field" is a term used to refer to a single site of hydrothermal emission surrounded by ordinary deep-sea bottom. The subterranean plumbing of different vent fields may be interconnected, thus fuelling more than one vent. See R Hessler and V A Kaharl, 'The Deep-Sea Hydrothermal Vent Community: An Overview', in S E Humphris et al., *Seafloor Hydrothermal Systems: Physical, Chemical, Biological, and Geological Interactions* (1995), 72.

[46] Van Dover, above n 33, 56.

[47] Van Dover, above n 33, 57.

Whereas others, such as TAG, are several kilometres away from the neovolcanic zone.[48]

The geological setting also determines the life of a particular hydrothermal vent. Thus on fast-spreading ridges, cycles of volcanism mean that individual chimneys or areas can be active for only a few decades or less.[49] However, radiometric dating on some currently active vents record venting for much longer periods of time. For example, research at the Main Endeavour Field indicates that individual vents can remain active in excess of 200 years.[50] Entire fields can remain active for much longer periods. The TAG field on the Mid-Atlantic Ridge, for example, appears to have been intermittently active for the past 40 000 to 50 000 years.[51]

One further very important physical aspect worth noting in relation to black smokers is their plumes. As hydrothermal fluids exit the opening or orifice of the black smoker they rise buoyantly, drawing in cold water and creating a widening column of turbulent eddies full of black hydrothermal precipitates or smoke.[52] Eventually the plume rises to a level where it is carried away by ocean currents.[53] These plumes play a very important role in the hydrothermal vent ecosystem, being one of several distinct microbial habitats associated with hydrothermal vents.[54]

[48] Van Dover, above n 33, 57.
[49] Ibid.
[50] Ibid.
[51] Ibid.
[52] Van Dover, above, n 33, 99.
[53] Ibid.
[54] This is discussed in more detail below in the context of the ecology of the hydrothermal vent ecosystem.

THE BIODIVERSITY OF THE DEEP-SEA.

Scientific interest in the deep-sea and what lies below it can be traced back for more than 2000 years.[55] However, for the period from the ancient Greeks up until the work of the Challenger Expedition in the nineteenth century, understanding of the biodiversity of the deep-sea was at best patchy and largely a matter of conjecture. By the mid nineteenth century work by the likes of the Norwegian naturalist G.O. Sars suggested that the deep-sea was home to more than just mythical sea monsters. Sars identified nearly 100 species of invertebrates living at depths greater than 600 metres.[56] In contrast Edward Forbes proposed the concept of the "azoic zone" (ie depths greater than 0.6 kms) below which no life was thought to exist.[57] For many years controversy raged as to who was correct, Sars or Forbes.

The Challenger Expedition from 1872 to 1876 settled this debate. An expedition of truly monumental proportions covering 69,000 nautical miles, it hauled samples from the ocean floor at 240 different locations.[58] After nearly 3 ½ years at sea and a 34

[55] M Deacon, *Scientists and the Sea: 1650-1900: a study of marine science* (1971).
[56] Gage and Tyler, above n 13, 3.
[57] Gage and Tyler, above n 13, 4.
[58] H L Burstyn, 'Big science in Victorian Britain. The Challenger Expedition (1872-6) and its Report (1881-95)' in M Deacon, T Rice and C Summerhayes, (eds) *Understanding the Oceans. A century of ocean exploration* (2001), 50.

volume report it established that the deep-sea was not a zone of zero life.[59] However the extent of species diversity in the deep-sea was still unclear.

From the work of the Challenger expedition up until the late 1960s it was believed that the deep-sea was only occupied by a small number of specialised species.[60] Work by Howard Sanders and Robert Hessler in the 1960s confirmed that, contrary to previous understanding, there was an increasing diversity of life the greater the depth of the ocean.[61] In a controversial publication they argued that the diversity of life in the deep-sea globally was probably in the vicinity of 10 million species.[62] As one scientist has noted, probably "more than enough species to rival the celebrated diversity of tropical rainforests".[63]

Over the last 40 years Sanders and Hesslers' estimation has remained controversial. Some have argued that species diversity is unlikely to exceed half a million.[64] Others have argued that species diversity is in fact far greater than Sanders and Hesslers' estimate.[65] While it is now clear that it is a species rich environment, we simply do not yet know enough about the deep-sea to know the full extent of its species

[59] Gage and Tyler, above n 13, 6.
[60] Van Dover, above, n 33, 8.
[61] Ibid.
[62] Ibid.
[63] Ibid.
[64] G C Poore and G D Wilson , 'Marine species richness' (1993) 361 *Nature* 597
[65] J F Grassle and N J Maciolek, 'Deep-sea species richness: regional and local diversity estimates from quantitative bottom samples' (1992) 139 *American Naturalist* 313.

diversity. This is due in large part to the fact that less than 0.001% of the deep-sea floor has been subject to biological investigation.[66] As one scientist has suggested

> "the state of our knowledge about what's down there is about what we would know of terrestrial creatures if we studied them by dropping grappling hooks from hot air balloons at night, bringing up only policemen [sic] and postmen [sic]".[67]

While we now know that the deep-sea is species rich many of these species are spread out amongst the vast expanse of the soft sediments of the sea floor.[68] In contrast to the sparsely populated soft-sediments of other areas of the deep-sea, hydrothermal vents have been found to be literally teeming with life.[69] They host one of the highest levels of animal abundance on Earth.[70] It is hardly surprising therefore that terms such as "oases of the abyss",[71] the "Oceanic Gardens of Eden",[72] and "biological islands"[73] have all been applied to describe these amazing deep-sea communities.

Hydrothermal vents have been shown to exhibit a unique range of habitat diversity with species so adapted to their particular niches that they are not paralleled at other sites on the planet.[74] They support amazingly diverse and rich ecosystems with high levels of biodiversity and high levels of endemism. Of the approximately 500 species

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[66] M C Baker etal 'An environmental perspective' In WWF/ IUCN, *The Status of natural resources on the high seas* (2001), 5.
[67] C L Dybas, 'The deep-sea floor rivals rain forests in diversity of life' (1996) 26 *Smithsonian* 96, 100.
[68] A J Butler et al, *A Review of the Biodiversity of the Deep Sea (2001),* 11.
[69] Van Dover, above n 33, 19.
[70] Baker et al, above n 66, 18.
[71] Ré, above n 23, 70.
[72] C H Allen, 'Protecting the Oceanic Gardens of Eden: International Law Issues in Deep Sea Vent Resources Conservation and Management' (2001) 13*Georgetown International Environmental Law Review* 563.
[73] Baker et al, above n 66, 18.

[74] Baker et al, above n 66, 18.

discovered around hydrothermal vents to date, it is believed that somewhere between 80%[75] to 90%[76] are endemic to hydrothermal vents and new to science.[77] Three phyla dominate and constitute 92% of the species identified: molluscs (34%), anthropods (35%) and annelids (23%).[78] In addition 32 octopus and fish species have also been observed in and around hydrothermal vents.[79] Individual species include giant clams, mussels, the giant tube worm *(Riftia pachyptila),* brachyuran crabs, galatheid crabs, turrid gastropods, limpets, polychaetes, pink bythitid vent fish,[80] barnacles, brittle stars, sea stars, anemones, sponges, soft corals[81] , hairy snails (*Alviniconcha hessleri*),[82] and jellyfish.[83]

While the total number of new species discovered is high, at individual vent sites local species diversity is typically low with dominance by a few species at each site.[84] Over 75% of vent species occur at only one site.[85] This endemism may mean that species are restricted to individual vent sites. What limited information that is available also suggests that different biogeographic hydrothermal provinces exist between vents. Different oceans such as the Atlantic and Pacific support quite different biological communities. For example, vent sites in the Atlantic Ocean are

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75 Dando and Juniper, above n 15, 2.
76 Baker et al, above n 66, 16.
77 Baker et al, above n 66, 16.
78 V Tunnicliffe, A G McArthur and D McHugh, 'A biogeographical perspective of the deep-sea hydrothermal vent fauna' (1998) 34 *Advances in Marine Biology* 355, 364.
79 Baker et al, above n 66, 16.
80 R A Lutz and M J Kennish, 'Ecology of deep-sea hydrothermal vent communities: A review' (1993) *31(3)Reviews of Geophysics* 211, 211-214.
81 Lutz and Kennish, above n 80, 221-223.
82 Lutz and Kennish, above n 80, 227.
83 R D Ballard, *The Eternal Darkness: A Personal History of Deep-Sea Exploration*, (2000), 184.
84 Butler et al, above n 68, 5.
85 Butler et al, above n 68, 5.

characterised by an abundance of shrimp whereas those in the Pacific are dominated by vestimentiferan tubeworms. Very few species have been found in more than one ocean.[86]

The discovery of so many species raised the question of how it was possible for all this life to survive. As one of the scientists involved in the initial discoveries noted

> "From the moment we first saw a bed of gigantic, living clams in 1977, one obvious question engaged everyone's mind: How can these creatures flourish at such depths, in an environment totally devoid of sunlight? To find out, researchers needed to trace the food chain from top to bottom, back to the primary producers. On the earth's surface, the primary producers are photosynthesizing plants and microbes. Using solar energy to set off a chain of chemical reactions, they convert carbon dioxide and other nutrients into the organic molecules in living tissues. But what was the ultimate energy source in the deep, dark abyss, and what were the nutrients."[87]

What scientists have subsequently confirmed is that the food chain of the hydrothermal vent ecosytem is based upon chemosynthetic microbial processes rather than photosynthesis.[88] In essence, the geological and geochemical processes responsible for forming the mid-oceanic ridges and hydrothermal vents also provide the food upon which the associated ecosystem thrives. Microbes thrive in the extremes of heat, pressure, and the unusual chemistry of the hydrothermal vents. These microbial forms of life oxidise sulphides, together with other chemicals released from hydrothermal vents such as hydrogen, iron or manganese.[89] These microbes thus serve as the base of the hydrothermal vent food chain.[90]

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[86] Baker, above n 66,18
[87] Ballard, above n 83, 178.
[88] J A Baross and S E Hoffman, 'Submarine Hydrothermal Vents and Associated Gradient environments as sites for the origin and evolution of life' (1986) 2 *Naval Research Reviews* 2, 6.
[89] Baross and Hoffman, above n 88.
[90] Many of these microbes have formed symbiotic relationships with several other species. In fact most species associated with hydrothermal vents gain sustenance from these microbes in one form or

In addition to supporting an amazing diversity of life, it is also worth noting that hydrothermal vent sites host one of the highest levels of microbial diversity on earth.[91] Around hydrothermal vents major habitat distinctions within vent fields are made on the basis of oxygen availability (ie aerobic or anaerobic), temperature and mien (ie microorganisms suspended in the water column or microorganisms attached to rocks, sediment, animals etc).[92] In terms of temperature, microbes can be categorised depending upon the temperature of the location in which they are found. These categories are superthermophilic (ie temperatures greater than 115°C), hyperthermophilic (80-115°C), thermophilic (50-80°C), mesothermophilic (10-50°C) and psychrophilic (ie less than 10°C).[93] Superthermophiles, hyperthermophiles and thermophiles are of intense interest because of the potential they offer for developments in biotechnology.[94] Black smokers are also known to generate plumes which provide an additional distinctive microbial habitat.[95] Some examples of the different miens for microbes are shown in Figure 3 below.

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another. Examples of such species include the tubeworms and some species of clams and mussels. Tube worms, which have no eyes, mouth or digestive tract, rely on these symbiotic bacteria to survive. They absorb oxygen and other inorganic compounds from the water, which the microbes living inside them use to absorb compounds for chemosynthesis. Tube worms are often therefore found in the area just above vent openings clustering in thickets to direct the exiting fluids past the tips of their tubes. Both tube worms and giant clams have been found to contain high amounts of hemoglobin, the oxygen-binding molecule also found in human and other mammals' blood. See Ballard, above n 83, 182 and Baross and Hoffman, above n 88.

[91] Canada, Department of Fisheries and Oceans *Endeavour Hydrothermal Vents Marine Protected Area Management Plan* (2001), 5.

[92] Van Dover, n 33, 122.

[93] Van Dover above n 33, 122.

[94] The nature of the biotechnology interest in these microbes is discussed in Chapter 7.

[95] Plumes are important as zones of chemical reaction between vent fluids and seawater, as habitat and resources for microorganisms zooplankton, and they also have a role to play in dispersal stages of vent biota. In addition, variations in vent chemistry are known to impact on the nature of particular

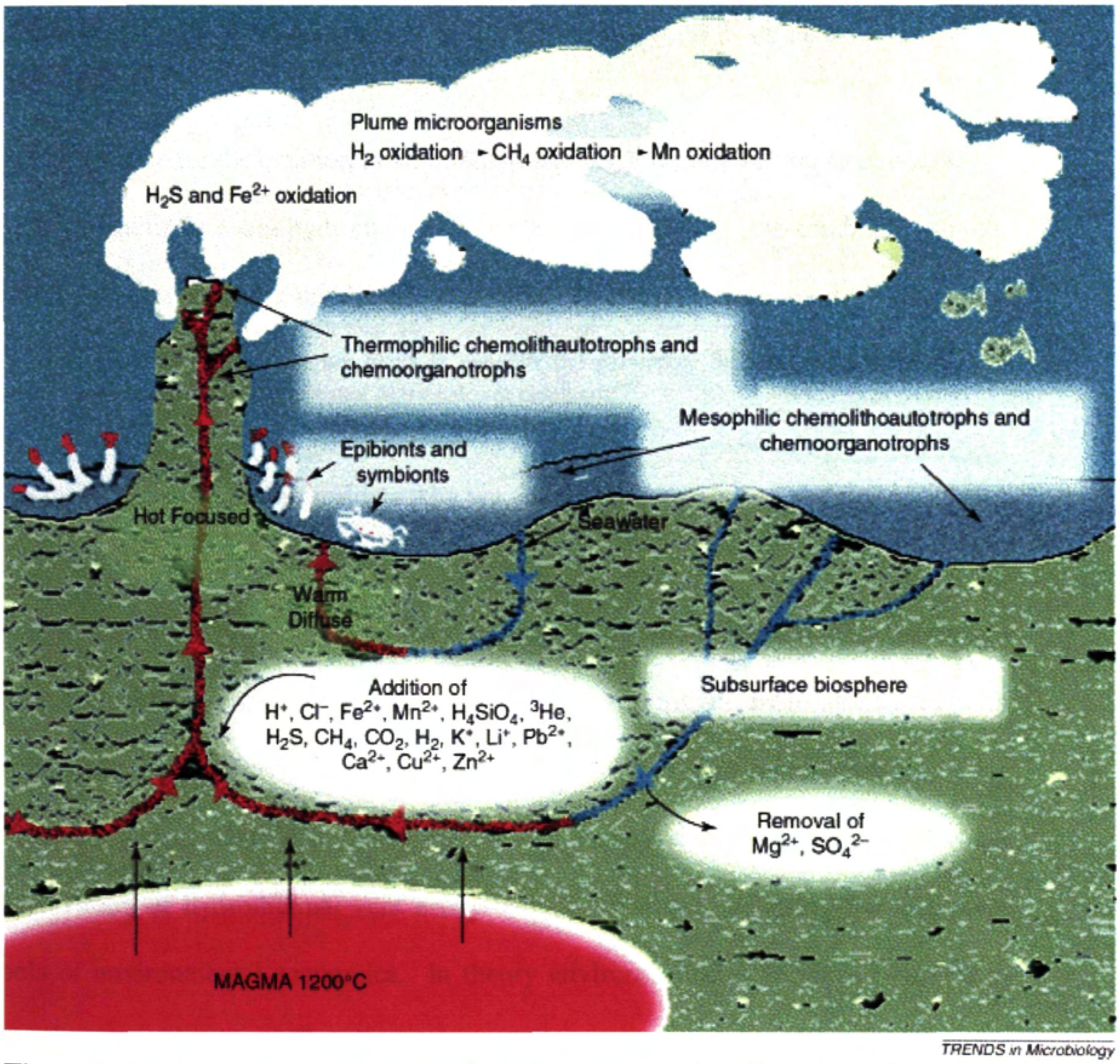

Figure 3: Diagrammatic representation of a cross section through a deep-sea hydrothermal system depicting the possible niches for different microbial communities.[96]

microbial communities. For detailed discussion of different microbial communities see Van Dover above n 33, 122.

[96] Reproduced from A L Reysenbach and S L Cady, 'Microbiology of ancient and modern hydrothermal systems' (2001) 9(2) *Trends in Microbiology* 70, 81.

WHAT IS SO IMPORTANT ABOUT THE HYDROTHERMAL VENT ECOSYSTEM? WHY BOTHER?

To build a case for the creation of an international legal regime for the sustainable management of deep-sea hydrothermal vents the very first step is to establish a sound case for such measures in the first place. As one commentator has noted

> "hyperthermophiles are not likely to generate the passionate lobbying support enjoyed by charismatic mega-vertebrates, like whales or elephants"[97]

The following discussion considers why we should bother.

The most detailed publication to date that has considered this question originated from a workshop organised jointly by scientists working in areas associated with hydrothermal vents, environmental NGO's such as WWF and representatives of the Canadian government.[98] In this publication a *raison d'etre* or rationale for the preservation of hydrothermal vent ecosystems is presented, adopting the analytical tools of environmental economics. In theory environmental economics is useful in assisting to identify efficient [sic] natural-resource management options for sustainable development.[99] It has been argued that environmental economics acts as

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[97] P S Sochaczewski and J Hyvarinen, 'Down Deep: Environmentalists Fight to Protect The Fantastic Microscopic Creatures That Dwell on the Ocean's Bottom' (1996) 7 *The Environmental Magazine* 15, 20.

[98] See Dando and Juniper, above n 15, 4-5.

[99] The foundation of such an approach is allocating an economic value to physical and biological resources. The total economic value of a resource is said to consist of its use value and non-use value. Use values are further broken down into the direct use value, the indirect use value and the option use (potential use) value. See M Munasinghe, 'Biodiversity Protection Policy: Environmental Valuation and Distribution Issues' (1992) 21(3) *Ambio* 227, 228.

an essential bridge between more traditional [sic] techniques of decision making and what is said to be an "emerging more environmentally sensitive [sic] approach".[100]

The use of environmental economics as an analytical tool has been subject to considerable criticism. Borgese has suggested that applying the language and the logic of environmental economics is "bizarre".[101] Environmental economics struggles to quantify and monetarize the value of environmental goods and services and force them into the market system. It is therefore not an appropriate analytical tool to utilise in the context of oceans management.[102] Accordingly it has been suggested that problems of ocean management should be approached not from an economic viewpoint but rather from an ethical one.[103] Borgese argues

> "it would be difficult indeed not to recognise that the world ocean, covering 70% of our planet and over 90% of the biosphere, is an essential part of our life support system. In the light of the magnitude of this fact, monetary considerations appear puny. All we can appeal to is our ethical obligation to conserve our life support system"[104]

However, it is possible to reconcile both approaches when considering why we should provide for the sustainable management of hydrothermal vents sites. It is true that these sites have an economic value, but they also have an intrinsic value that extends beyond their mere economic value, which is not easily quantified. Adopting a much more holistic approach beyond that of environmental economics, it is possible to argue that the need for a regime for the sustainable development of hydrothermal

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[100] Munasinghe, above n 99.
[101] E M Borgese, 'The economics of the common heritage' (2000) 43 *Ocean & Coastal Management* 763, 771.
[102] Borgese, above n 101.
[103] Borgese, above n 101.
[104] Borgese, above n 101, 772.

vents beyond national jurisdiction is justified on three main grounds: firstly, their importance in terms of advancing important scientific and philosophical debates; secondly, the potential economic value of the resources associated with hydrothermal vents; and finally, the importance of hydrothermal vents in terms of the conservation of biodiversity, which it is argued should be regarded as the primary reason for implementing measures for their sustainable management. This later reason is the most significant because emerging threats to these ecosystems have already been identified, albeit they are currently vaguely quantified. Each of these justifications is considered below.

Hydrothermal vents and two "big questions': The origin of life and the search for life elsewhere in the universe

Hydrothermal vents have been of immense interest to a range of different scientific disciplines since their discovery. The nature of scientific research is considered in more detail in Chapter 8. However, one of the most interesting scientific developments to have arisen as a consequence of the discovery of hydrothermal vent ecosystems is their impact on the scientific debate as to the origin of life on earth, and the search for life elsewhere in the universe.

The question of how life first started on earth is perhaps one of the greatest unanswered questions of all times. Countless philosophers, theologians and scientists have considered this over time. The likes of Aristole, Thomas Aquinas, Descartes, Francis Bacon, Charles Darwin, to mention but a few, have all in one way or another considered this great unanswered question.[105] This debate is by no means concluded. The great unanswered question still remains unanswered, but the discovery of the hydrothermal vent ecosystem, driven as it is by chemosynthetic micro-organisms, has given rise to a new theory as to how life originated on earth. That is that life on earth could very well have originated and evolved in association with hydrothermal vents in the primeval ocean during the early Archaean period (approximately 4,000 million years ago).[106] In some respects that theory draws on the earlier work by the likes of Charles Darwin, Alexander Oparin and J.B.S. Haldane.[107]

The origin of life at hydrothermal vents?

In the *Origin of the Species*[108] Charles Darwin posited the notion that all species are descended from common parents and that differences in individual species arose through the processes of natural selection. In that context Darwin in part illustrates his hypothesis by means of a diagram adopting the metaphor of a tree.[109] He first uses it to represent the divergence of variants within a species, showing successively more difference in a single lineage and splitting into multiple lineages, some of which will become new species.[110] Later, he expands the tree metaphor, explaining that

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[105] For a detailed discussion and overview of the contribution of these and other great thinkers see I Fry *The Emergence of Life on Earth: A Historical and Scientifc Overview* (2000).

[106] JA Baross and S E Hoffman, 'Submarine Hydrothermal Vents and Associated Gradient environments as sites for the origin and evolution of life' (1986) 2 *Naval Research Reviews* 2.

[107] Discussion of this issue in large part draws on the summary of this theory and subsequent developments provided in R Ellis, *Aquagenesis. The Origin and Evolution of Life in the Sea* (2001), 9-16.

[108] C Darwin, *The Origin of Species by means of natural selection or the preservation of favoured races in the struggle for life* (1901).

[109] W F Doolittle, 'Phylogenetic Classification and the Universal Tree', http://cas.bellarmine.edu/tietjen/Ecology/phylogenetic_classification_and_.htm (last accessed 3/4/03)

[110] Doolittle, above n 109.

> "limbs divided into great branches ... were themselves once, when the tree was small, budding twigs; and this connection of the former and present buds by ramifying branches may well represent the classification of all extinct and living species in groups subordinate". [111]

Darwin's metaphor of a tree suggests that all life on earth had a common ancestor. As Darwin observed

> "I believe that animals have descended from at most only four or five progenitors, and plants from an equal or lesser number. Analogy would lead me one step further, namely, to the belief that all animals and plants have descended from some one prototype...all living things have much in common, in their chemical structure, and their laws of growth and reproduction. We see this even in so trifling a circumstance as that the same person often similarly affects plants and animals; or that the poison secreted by the gall-fly produces monstrous growths on the wild rose or oak-tree. Therefore I should infer from analogy that probably all the organic beings which have ever lived on this earth have descended from some one primordial form, into which life was first breathed".[112]

The *Origin of the Species* was a controversial publication and Darwin's theories were subject to intense criticism. Despite the controversial nature of Darwin's assertions towards the middle of the twentieth century the question of the origin of life had become a legitimate scientific discourse worthy of further research.[113] The most significant subsequent development was what is now known as the Oparin-Haldane hypothesis. Both Alexander I. Oparin and J.B.S. Haldane, working independently of each other, claimed "that a necessary step on the way to life was the abundant synthesis of organic compounds on the primordial Earth" and they set out a hypothesis as to "the geophysical conditions on the ancient Earth and the constituents of the early atmosphere that made this synthesis possible".[114]

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[111] Doolittle, W.F. "Phylogenetic Classification and the Universal Tree", http://cas.bellarmine.edu/tietjen/Ecology/phylogenetic_classification_and_.htm accessed 3 April 2003.

[112] Darwin, above n 108, 371-372.

[113] Fry, above n 105, 6.

[114] Fry, above n 105, 65.

The discovery of the hydrothermal vent ecosystem driven by chemosynthesis has given rise to a new theory as to the origin of life, which implies that an environment much like that found in hydrothermal vents was responsible for the origin of life on earth. In some respects this theory draws upon the intellectual legacy of Darwin, Oparin and Haldane. The hydrothermal vent hypothesis has been put forward by John Baross and Sarah Hoffman.[115] Baross and Hoffman formulate the question as to the origin of life in the following terms

> "what environments could provide all of the physical and chemical conditions for the sequence of reactions leading to organic compounds, self replicating and information-carrying macromolecules, and eventually organisms and ecosystems".[116]

They go on to propose that

> "life developed and evolved in a primeval shallow ocean in association with the multiplicity of gradients resulting from the interactions between variables now known to have been important during the early Archaean: the tectonism associated with seafloor spreading, the resultant hydrothermal alteration of newly-emplaced oceanic crust, and the composition of the ocean and atmosphere of the early Earth".[117]

If this theory is correct then life on earth originated in an environment very similar to that found at deep-sea hydrothermal vents today.

It is unlikely that we will ever know if this hypothesis is correct or not. It has been criticised by other scientists such as Miller and Bada,[118] who reject the hypothesis outright. However, the hypothesis is consistent with other evidence. Three particular

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[115] See JA Baross and S E Hoffman, 'Submarine Hydrothermal Vents and Associated Gradient environments as sites for the origin and evolution of life' (1986) 2 *Naval Research Reviews* 2.
[116] Baross and Hoffman, above n 115, 3.
[117] Ibid.

[118] S L Miller and J L Bada, 'Submarine hot springs and the origin of life' (1988) 334 *Nature* 609.

areas are worthy of note: work by microbiologists in relation to position of thermophiles found in hydrothermal vents within the "universal tree of life"; recent work by geologists working in the Pilbara region of Western Australia; and more recently emerging evidence as to the origin of the genetic code or DNA.

Until 1977 scientists divided life on earth into two primary kingdoms; the Prokaryotes and the Eukaryotes. In a seminal paper first published in 1977 Woese and Fox [119] proposed a radical restructuring of this fundamental phylogeny of life. Based on detailed comparisons of 16S and 18S rRNA sequences, the two primary kingdoms were partitioned into three discrete domains, named as the Eukaryotes, the Eubacteria and the Archaebacteria.[120] Subsequent work by Woese[121] revised this system of nomenclature and it is now suggested that all life on earth could be broken into three main domains : the Archaea, Bacteria and Eucarya.[122] This system of nomenclature is illustrated below in Figure 4.

[119] C R Woese and G E Fox, 'Phylogenetic structure of the prokaryotic domain: the primary kingdoms' (1977) 91 *Proceedings of the National Academy of Science* 1810.
[120] D A Cowan, 'Hyperthermophilic enzymes: biochemistry and biotechnology' in L M Parson and C L Walker, et al(eds) *Hydrothermal Vents and Processes* (1995), 351-352.
[121] C R Woese, O Kandler and M L Wheelis, 'Towards a natural system of organisms: proposals for the domains Archaea, Bacteria and Eucarya' (1990) 87 *Proceedings of the National Academy of Science* 4576.
[122] D A Cowan, above n 120, 352.

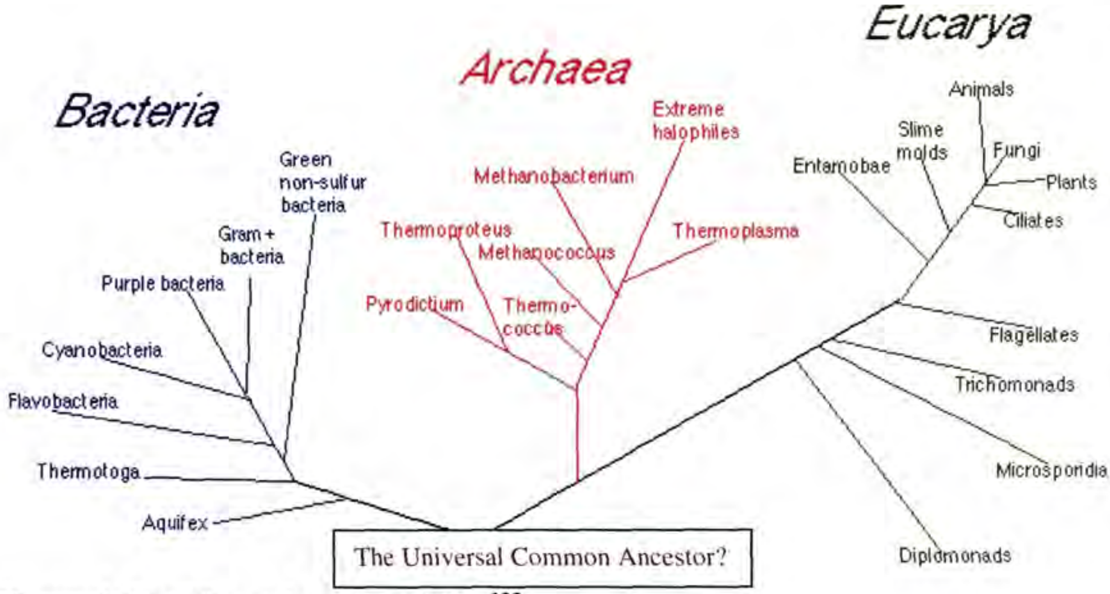

Figure 4: The Three domains of life.[123]

Comparison of the RNA sequences has led to the discovery of some interesting patterns. If it is accepted that all forms of life had one common ancestor as Darwin alluded to, then bacteria and archaea appear to be the closest to this common ancestor of all life. The heat-loving bacteria and archaea, the hyperthermophiles, appear to be nearest to the common ancestor of all life on earth.[124] This tends to suggest that hydrothermal systems may have been a cradle for early biosphere evolution.[125] The most primitive thermophiles are all chemosynthetic organisms that use hydrogen and sulphur in their metabolism.[126] Modern hydrothermal vents may therefore serve as refuges for close relatives of ancient forms of life.[127] This assumes, however, that

[123] Adapted from http://www.biologie.uni-hamburg.de/b-online/library/micro229/terry/229sp00/lectures/taxonomy.html accessed 7 April 2003.
[124] J D Farmer, 'Hydrothermal Systems: Doorways to Early Biosphere Evolution.' (2000) 7 *GSA Today* 1.
[125] Ibid.
[126] Ibid.

[127] Ibid.

there are only three branches of the tree, and that what we are seeing is the base of this tree, and not merely the base of the limb of a much bigger tree, the rest of which is now extinct. Indeed the structure of the tree of life may be far more complicated than can be confirmed at this stage.[128]

However, support for the idea of the origin of life in an environment similar to modern hydrothermal vents is also slowly emerging from the geological record, although the evidence is by no means conclusive. In 2000 Rasmussen reported the discovery of pyritic filaments contained in a 3,235 million year old deep-sea volcanogenic massive sulphide deposit from the Pilbara Craton, Western Australia.[129] These pyritic filaments have been interpreted by Rasmussen as the fossil remains of thread-like micro-organisms. The implication is that these were chemotrophic hyperthermophiles which lived at or near 100 °C.[130] The discovery of these probable microfossils suggests that a chemotrophic deep-sea hydrothermal biosphere thrived over 3,235 million years ago, some 2,700 years earlier than previously known.[131] This does lend circumstantial support to the argument that steps in the early history of life took place around hydrothermal systems.[132]

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[128] For discussion on this see W F Doolittle, 'Phylogenetic Classification and the Universal Tree', http://cas.bellarmine.edu/tietjen/Ecology/phylogenetic_classification_and_.htm accessed 3 April 2003 and W Martin, 'Mosaic bacterial chromosomes: a challenge en route to a tree of genomes' (1999) 21(2) *BioEssays* 99.

[129] B Rassmussen, 'Filamentous microfossils in a 3,235-million-year-old volcanogenic massive sulphide deposit' (2000) 405 *Nature* 676.

[130] E Nisbet, 'The realms of Archaean life' (2000) 405 *Nature* 625.

[131] Rassmussen, above n 129, 679.

[132] Nisbet, above n 130, 626.

Finally it is worth noting that some evidence suggests that the genetic code or DNA may have originated in a high pressure environment such as that associated with hydrothermal vents.[133]

Hydrothermal vents and the search for life in outer space.

> "At least since the time of the ancient Greeks, inquiring minds have wondered whether we are alone in the universe, and since that time the question has been a frequent companion to science and philosophy."[134]

Like the origin of life the search for life beyond earth is a philosophical and scientific question that humanity has considered for millennia. Current scientific thinking suggests that the search for signs of life in outer space should concentrate, not on the search for radio waves from space or UFO's, but instead on the search for traces of thermophilic micro-organisms on Mars. This strategy is premised on the assumption that hydrothermal systems similar to those found on earth may also have at one time existed on Mars. On earth thermophilic microorganisms have been found not only in hydrothermal vent sites on the deep-sea floor and those in shallower waters, but also in terrestrial biotopes such as sulphur containing solfaratic fields (ie soil, mud holes and surface waters heated by volcanic exhalations from magma chambers).[135] There is increasing evidence of the presence of water on Mars during its history and

[133] M D Giulio, 'The Ocean abysses witnessed the origin of the genetic code' (2004) *Gene* (in print), advance draft on file with author.
[134] S J Dick, *The biological Universe: The Twentieth-Century Extraterrestrial Life Debate and the Limits of Science* (1996), I.
[135] K O Stetter, 'Hyperthermophilc Organisms' in G Horneck and C Baumstark-Khan (eds) *Astrobiology: The Quest for the Conditions of Life,* (2002), 170-171.

possibly still today.[136] Locating possible sites for hyperthermophiles therefore involves identifying sites which indicate both an aqueous environment and volcanic heat sources such as hydrothermal vents. This is what NASA is looking for in the Mars Exploration Rover Mission currently exploring Mars.[137]

Mars is not the only planet that is currently being investigated for signs of life. It has been suggested that active hydrothermal vent systems exist on Jupiter's Moon Io and Mar's Moon Europa.[138] Images sent back to earth by the Galileo spaceship clearly show active volcanoes and possibly hot springs on Io. Until mid 2002 NASA was in the early stages of preparation of a mission to Europa scheduled for 2008 to confirm the presence of an ocean on Europa. A subsequent mission was also planned with the specific purpose of searching for hydrothermal vents and possibly life. However, budgetary cutbacks mean this project has been suspended.[139]

Significance of cosmic proportion

> "the map of life's early evolution grows ever more detailed as new terrains are inked in...the map is still medieval in aspect, with large blank areas marked 'Terra incognita', or 'Here be cannibals. And we still know little about the far edge of the world of life- where did it come from".[140]

[136] See for example R A Kerr, 'Making a Splash with a hint of Mars Water'. (2000) 288 *Science* 2295 and M C Malin and K S Edgett (2000) 'Evidence for Recent Groundwater Seepage and Surface on Mars', (2000) 288 *Science* 2330.
[137] See NASA web site http://www.nasa.gov/vision/universe/solarsystem/mer_main.html , accessed 10 October 2002.
[138] For further details see NASA web sites http://science.nasa.gov/newhome/headlines/ast30sep99_1.htm and http://antwrp.gsfc.nasa.gov/apod/ap970818.html accessed 10 October, 2002.
[139] See NASA web site in relation to this project http://www.jpl.nasa.gov/europaorbiter/ accessed 10 October, 2002.

[140] Nisbet, above n 130, 626.

No one yet knows what the result of ongoing research into the origin of life or the search for life in outer space may be. However, the potential that hydrothermal vent species, in particular bacteria and archaea, have in assisting us to answer either of these great scientific questions means that hydrothermal vents, and the microbes that inhabit them are potentially organisms of purely cosmic importance. The implications for humanity in discovering how life began or indeed that there is life on other planets would be profound.[141] If current scientific research leads to an answer to either of these "big questions", the discovery and research into the microbial life that inhabits hydrothermal vents may well have led to these discoveries. A truly grand achievement for such an unpretentious and minute form of life!

Given the significance to all of humanity of solving these great unanswered questions this, of itself, quite apart from any other reasons, provides strong justification for a strict application of the precautionary principle which would dictate that all human intervention in these ecosystems proceeds with care.

Potential Economic value of hydrothermal vent resources

Given the extreme environment in which hydrothermal vents are found, it is perhaps surprising that there could possibly be interest in the exploitation of hydrothermal vents for commercial purposes. Extreme pressure, extreme temperatures, total darkness and the sheer logistical difficulties of getting to individual vent sites would suggest that hydrothermal vents would not be a prime target of trade and commerce.

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[141] For detailed discussion of both the scientific significance and the philosophical significance of answering either of these questions see for example P Davies, *The Fifth Miracle. The Search for the Origin of Life*, (1998).

Such an assumption is incorrect. Hydrothermal vents present a huge potential (and in some cases an actuality) for exploitation for commercial purposes. Four main commercial activities are worth noting. These are bioprospecting, deep-sea mining, deep-sea adventure tourism, and geothermal energy.

The nature and extent of bioprospecting at hydrothermal vents and developments in biotechnology are canvassed in detail in Chapter 7. Deep-sea mining is discussed in part in Chapters 6 and 9, and accordingly discussion of both these activities is best left until then.

Of far less economic significance is the emerging market for deep-sea tourism. The deep-sea would not typically be regarded as a prime holiday destination. For those tourists jaded by the world's other travel destinations until recently the only remaining frontier destinations were the Antarctic[142] and Space.[143] However, the deep-sea now appears to be a new and emerging adventure tourist destination.

Deep Ocean Expeditions LLC[144] currently appears to be the main company actively involved in deep-sea tourism, although that company does not like to call its

[142] Antarctica arguably can no longer be regarded as such given the number of tourists who visit Antarctica each year. For example, in the 2001-2002 season in excess of 11,000 tourists set foot on Antarctica. See International Association of Antarctica Tour Operators web site http://www.iaato.org/tourismstatistics/index.html accessed 16 April 2003.

[143] American businessman Dennis Tito became the first paying space tourist in April, 2001 with his visit to the International Space Station as part of a Russian mission.

[144] Hereinafter DOE.

customers tourists but instead "expedition participants".[145] DOE is a company incorporated in the Isle of Man.[146] It was established in 1998 by Australian adventurer Mike McDowell, who has been active in a range of adventure tourist expeditions including the first tourist expeditions to the North Pole using Russian nuclear icebreakers, expeditions to the Antarctic continent and space travel.[147]

DOE was the first company to develop a new form of tourism which it calls "Adventure Diving". Since its establishment in 1998 the company has taken tourists or expedition participants on dives to depths as shallow as 300 feet and as deep as 17,000 feet (about half the greatest depth in the ocean).[148] These dives have been to a range of different locations including the wreck of the *RMS Titanic* in the Atlantic Ocean and the wreck of the German battleship *Bismarck* off the Irish Coast. DOE has also been involved with the filming of several impressive documentaries in the deep-sea, including the innovative high definition 3D production in relation to the wreck of the Titanic, *Ghosts of the Abyss*, directed by James Cameron, as well as several other documentaries produced by the BBC and the Discovery Channel. DOE and James Cameron also recently produced an IMAX documentary on hydrothermal vents,

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145 See Deep Oceans Expeditions web site http://www.deepoceanexpeditions.com accessed 23 December 2004.

146 Interview, Belinda Sawyer, Operations Manager, Deep Ocean Expedition, Queenstown New Zealand 5 December 2003.

147 Deep Oceans Expeditions web site http://www.deepoceanexpeditions.com accessed 23 December 2004.

148 Deep Oceans Expeditions web site http://www.deepoceanexpeditions.com accessed 23 December 2004.

"Volcanoes of the Deep Sea" which involved co-operation with inter alia scientists associated with Macquarie University and the Australian Centre for Astrobiology.[149]

To date more than 40 people have been taken to deep-sea hydrothermal vents on expeditions organised by DOE.[150] Sites visited include hydrothermal vents in the Azores (such as Lucky Strike and Menez Gwen), Mid-Atlantic ocean sites such as Logatchev and sites in the Pacific Ocean such as 9 degrees North and 29 degrees North.[151] Participants in these expeditions have included nationals from the USA, Denmark, the United Kingdom, Germany, New Zealand and Costa Rica. One of the Australian participants of note was the author Thomas Keneally who took part in the expedition to 9 Degrees North from 31 August to 12 September 2003.[152]

The tours are not cheap. The average cost to participants is approximately $US20,000 to US$35,000 per person depending on the destination. This amount typically includes accommodation in hotels on shore, accommodation and meals on the vessel while in the ocean, a dive in a submersible to an active hydrothermal vent site, educational lectures by leading scientists and deep-ocean experts while on board

[149] Interview, Carol Oliver 11 February 2004, Australian Centre for Astrobiology and personal correspondence, Belinda Sawyer, Operations Manager, Deep Ocean Expedition, on file with author.
[150] Interview, Belinda Sawyer, Operations Manager, Deep Ocean Expedition, Queenstown, New Zealand 5 December 2003. DOE has also taken more than 100 people to the wreck of the RMS Titanic.
[151] Interview, Belinda Sawyer, Operations Manager, Deep Ocean Expedition, Queenstown, New Zealand 5 December 2003.
[152] Deep Oceans Expeditions web site http://www.deepoceanexpeditions.com accessed 23 December 2004.

the vessel, and a souvenir videotape of the dive. For those who do not wish to dive to hydrothermal vents the typical cost is approximately US$4,000.[153]

Significantly DOE lists its mission as involving three core principles:

- To offer unique expeditions for the adventurer;
- To educate people about the world's deep oceans; and
- To help support scientific research.

On face value it appears DOE conducts its expeditions consistent with these core principles. Education of participants and the wider public is at the core of DOE's activities. Examination of the impressive series of lectures and videos shown to participants on each cruise clearly shows the educational nature of the expeditions.[154] Similarly the production of documentaries by the likes of James Cameron for the BBC and the Discovery Channel can only enhance the understanding of the unique environment of the deep-sea by the wider community.

More significantly these expeditions are integrated into existing scientific research expeditions carried out by the PP Shirshov Institute of Oceanology, Russian Academy of Sciences. The expeditions organised by DOE utilise the Research Vessel R/V Akademik Keldysh and the *Mir* submersibles. In turn these expeditions provide an extra source of funding for Russian Scientists to carry out their research.

[153] Interview, Belinda Sawyer, Operations Manager, Deep Ocean Expedition, Queenstown, New Zealand 5 December 2003.

[154] For a detailed description of the educational component of these expeditions see the account of one participant on DOE's web site site http://www.deepoceanexpeditions.com accessed 23 December 2004.

This is significant in terms of the environmental impact of deep-sea tourism. As these tourist dives are integrated into scientific research dives this means that the environmental impact of such activities is indistinguishable from that of marine scientific research.[155] Given the clear educational value of these expeditions and, more importantly, the fact that there would appear to be no environmental impact separate from that of MSR, regulation of these activities does not appear to merit consideration at this stage. Provided MSR is regulated appropriately (and this is the subject of detailed discussion in Chapter 8), no regulation of the emerging deep-sea tourism is warranted at this time. Accordingly a detailed consideration of possible options for regulating deep-sea tourism will be excluded from further consideration in this thesis. If the nature of deep-sea tourism changes this issue may warrant re-examination at a later date.

Geothermal energy.

A further theoretical, but as yet unrealised economic value associated with hydrothermal vents is their potential use for generating hydrogen fuel.[156] So far there is no evidence to suggest that this is anything other than a theoretical possibility and accordingly this potential economic activity is also excluded from further consideration in this thesis.

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[155] Hereinafter MSR.
[156] Y V Bubis and Z N Molochnikov et al, 'Hydrogen Fuel Production in the Ocean using the Energy of "Black Smokers" (1993) 11 *Marine Georesources and Geotechnology* 259.

PRIMARY JUSTIFICATION-CONSERVATION OF BIODIVERSITY

Notwithstanding the value of hydrothermal vents to science and philosophy and their economic value, the most important reason for caring about what happens at hydrothermal vents is the need to conserve and sustainably manage biodiversity. The conservation of biological diversity on earth per se, quite apart from any benefits this may bring to humanity, has been recognised as a desirable objective in its own right. This is a fundamental principle underlying the CBD, which recognises the intrinsic value of biological diversity.[157] The recognition of the intrinsic value of biological diversity is significant because it may be seen as acknowledging the inherent right of all components of biodiversity to exist independent of their value to humankind.[158]

As the deep-sea constitutes the most typical habitat on earth and is where literally millions of species live,[159] we do need to take steps to conserve the biological diversity of this habitat, particularly where specific threats have been identified. Despite the environment in which these species are found, and notwithstanding the logistical difficulties for humans in accessing them, hydrothermal vent ecosystems and their associated and dependent species are under threat from human activity. The published literature has identified in general terms the main known threats to hydrothermal vents and their dependant ecosystems. The threats to hydrothermal vent ecosystems that have been identified are:

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[157] L Glowka and F Burhenne-Guilmin et al *A Guide to the Convention on Biological Diversity*, (1994), 9.

[158] Glowka and Burhenne-Guilmin above n 157.

- MSR;
- bioprospecting for genetic resources;
- deep seabed mining; and
- deep-sea tourism.[160]

Two further threats that have been noted but not considered in any detail are the impacts of pollution and the introduction of alien invasive species on deep-sea habitats.[161]

Review of the existing scientific, legal and policy literature during research for this thesis could not identify any detailed consideration of the scale and nature of these threats. For the foreseeable future though MSR, mining, and bioprosecting seem to be the most significant activities that may impact on hydrothermal vents,[162] even though these threats are to date largely vaguely understood and quantified. Further detailed scientific research on the nature of these threats is clearly warranted.

Despite the lack of detailed information about these threats, we should be concerned about the loss of species in the deep-sea and at hydrothermal vents just as much as in any other region or habitat on earth. Given the greater proportion of the earth's

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[159] J D Gage and P A Tyler, *Deep-Sea Biology: A natural history of organisms at the deep-sea floor* (1991).
[160] Dando and Juniper, above n 15, 6-8.
[161] Dando and Juniper, above 15.

[162] L Glowka, 'Testing the Waters: Establishing the Legal Basis to Conserve and Sustainably Use Hydrothermal Vents and Their Biological Communities" (1999) 8(2) *InterRidge News*.

species diversity that is found in the deep-sea, our concern for species of the deep-sea arguably should be just as great, if not greater, than other regions of the planet. With an emerging awareness that such threats do exist, the agreed objectives of biodiversity conservation and the intrinsic right of such species to exist recognised by the CBD, and adopting a precautionary approach, a shift in the focus of our efforts to the deep-sea and hydrothermal vent ecosystems in particular is justified.

In many respects the battle to shift the focus of the conservation debate to the deep-sea is a new frontier that brings with it many new challenges. Extremes of depth, pressure and darkness mean that this is an area of the planet that few people understand and of which even fewer have first hand experience. As such it poses unique difficulties for legal regulation.

CONCLUSION

It does appear that there is some conflict between conservation of the biodiversity of hydrothermal vents and some of the other reasons for bothering about the deep-sea and hydrothermal vents in particular. How can we take advantage of the growth in scientific knowledge that hydrothermal vents offer while ensuring that this important scientific research does not destroy the very ecosystem from which that knowledge may potentially come? Likewise how can we sustainably use the genetic and mineral wealth of hydrothermal vents? How international law should respond to these issues and the interests of the different stakeholders involved is at the core of this thesis. Before turning to these central issues Chapter 2 considers the existing status of hydrothermal vents and their sustainable management under international law.