Yves Fouquet · Denis Lacroix *Editors*

Deep Marine Mineral Resources

éditions Quæ
Éditions Cirad, Ifremer, Inra, Irstea
www.quae.com

Springer

Deep Marine Mineral Resources

Éditions Quæ

Matière à débattre et décider collection

Comportementsalimentaires
Choix des consommateurs et politiques nutritionnelles
Collective work
2012, 104 p.

Lobbying de l'agroalimentaire et normes internationales
Le cas du Codex Alimentarius
Maryvonne Lassalle-de Salins
2012, 264 p.

La France des friches
De la ruralité à la féralité
Annik Schnitzler and Jean-Claude Génot
2012, 208 p.

The world's challenge
Feeding 9 billion people
Marion Guillou and Gérard Matheron
2011, 240 p.

Les OGM à l'épreuve des arguments
Sylvie Berthier and Valérie Péan
2011, 218 pages

Pour une alimentation durable
Réflexion stratégique duALIne
Catherine Esnouf, Marie Russel, Nicolas Bricas
2011, 288 p.

Mieux combattre les marées noires
Michel Girin, EminaMamaca
2011, 192 p.

Éditions Quæ
RD 10
78026 Versailles Cedex, France www.quae.com

Yves Fouquet · Denis Lacroix
Editors

Deep Marine Mineral Resources

Springer

éditions Quæ
Éditions Cirad, Ifremer, Inra, Irstea
www.quae.com

Editors
Yves Fouquet
Centre de Bretagne - GM
Ifremer
Plouzané
France

Denis Lacroix
Ifremer Sète
Sète cedex
France

Éditions Quæ, R10,78026 Versailles cedex, France www.quae.com

ISBN 978-94-017-8562-4 ISBN 978-94-017-8563-1 (eBook)
DOI 10.1007/978-94-017-8563-1
Springer Dordrecht Heidelberg New York London

Library of Congress Control Number: 2013957486

© Éditions Quæ 2014
This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed. Exempted from this legal reservation are brief excerpts in connection with reviews or scholarly analysis or material supplied specifically for the purpose of being entered and executed on a computer system, for exclusive use by the purchaser of the work. Duplication of this publication or parts thereof is permitted only under the provisions of the Copyright Law of the Publisher's location, in its current version, and permission for use must always be obtained from Springer. Permissions for use may be obtained through RightsLink at the Copyright Clearance Center. Violations are liable to prosecution under the respective Copyright Law.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
While the advice and information in this book are believed to be true and accurate at the date of publication, neither the authors nor the editors nor the publisher can accept any legal responsibility for any errors or omissions that may be made. The publisher makes no warranty, express or implied, with respect to the material contained herein.

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Preface

Major industrial developments are based on the availability of energy and minerals: iron in the 19th century, aluminium and copper in the 20th century, silicon and high-tech metals for the past twenty years. Today, growing tensions are emerging between mineral availability and global requirements, especially in major industrial countries, which continue to rise in number and force. China's growth alone accounts for half of the rise in demand for base metals since 2000. Given the risks for Europe of supply shortages of strategic metals used in many high-tech industries, or even of certain common metals such as copper, it has become necessary to actively explore the potential of deep-sea mineral resources (DSMR), as a possible source in addition to known deposits on land.

It is with this as a backdrop that I decided to launch a study, in September 2009, on this subject with a 2030 vision, focusing on the needs of France and Europe. France boasts a vast ocean territory, technological resources and long recognised skills in deep-sea exploration; it is therefore important that France continues to be a major player in this exploration, especially at a time when the conditions governing industrial development of this sector are being defined.

Over twenty French partners, representing the sector's main players, were involved in this year-long study. I would like to thank them most sincerely for their investment in this collective effort. The issues addressed were both numerous and complex, as they concerned changes in the legal framework, supply and markets, the types of deep-sea geological sites liable to be exploited, the possible technologies and their impacts, all in an environment that remains poorly known and difficult to access.

Ifremer fully played its role in organising this collective study by calling upon public and private skills and expertise in a wide variety of fields, ranging from international law in the high seas to research and training. Like all good foresight studies, this work has given rise to proposals of concrete actions for all those concerned, in order that this collective effort may successfully serve our country.

Jean-Yves Perrot
Chief Executive Officer of Ifremer

Acknowledgements

Yves Fouquet and Denis Lacroix would like to thank all those involved in this two-year collective effort, if we include the time required to write up the results. First of all, we thank all the members of the Steering Committee, who were involved from the very beginning and who oversaw and guided all the work.

The members of the Working Group deserve special thanks, as they constantly contributed throughout the analysis, audit, discussion and summary process from start to finish, even during the write-up phase. These members are F. Bourse (Gerpa), D. Delorme (Areva), B. Martel-Jantin (BRGM), N. Bassaler (CAS), A. Cheilletz and J. Dyment (CNRS/INSU), J.-M. Montel and L. Filipov (ENSG Nancy), P. Cochonat, L. Lemoine and W. Roest (Ifremer), P. Barrier and O. Bain (Institut LaSalle-Beauvais), X. Foata (MEEDTL), F. Bersani (Méfi), F. Clin (MESR), F. Simard (IUCN) and M. Maia (UBO).

Our thanks also go to the experts consulted, who effectively supported both the work and debates: F. Brunet (CNRS/INSU), J.-L. Charlou (Ifremer), P. Espinasse (Technip), J. Galéron (Ifremer), O. Gauthier (MEEDTL), E. Gibert-Brunet (DGA), E. Jarmache (*Secrétariat général de la mer*), C. Lamiraux (MEEDTL), P. Masclet (DGA), C. Nouvian (consultant), V. Perrier (MEEDTL), A. Tatout (DGA) and I. Shepherd (EU/DG Industry).

We also extend warm thanks to the Communication team at Ifremer headquarters, and in particular the Director, Pascale Pessey-Martineau, and Vincent Schiltz, for their decisive assistance in the final formatting and publishing phase. Finally, we would like to acknowledge Mr. Antoine Valéry who contributed to reflection on legal and geopolitical aspects during the study presentation day at the *École des mines de Paris*, and Gilbert Troly, President of the *Société de l'industrie minérale*, the day's organiser.

Contents

Part I Study Summary

1 **Study Summary** 3
Yves Fouquet and Denis Lacroix

Part II Thematic Contributions

2 **Deep-sea Environment** 41
Joëlle Galéron

3 **Rare and Strategic Metals** 55
Yves Fouquet and Bruno Martel-Jantin

4 **Characteristics and Formation Process** 65
Yves Fouquet

5 **Scientific Knowledge and Challenges Related to Hydrogen** 87
Jean-Luc Charlou, Jean-Pierre Donval, Fabrice Brunet,
Manuel Munoz and Olivier Vidal

6 **International Law and Its Evolution** 95
Élie Jarmache

7 **Training Organisations and Establishments in France and Europe** 103
Alain Cheilletz and Marcia Maia

8 **Access to Raw Materials** 115
Antoine Valéry

9 **Conclusion** 121
Yves Fouquet and Denis Lacroix

Appendices 123

Bibliography 145

Associate Partners 149

Contributors

Fabrice Brunet Observatoire Terre-Univers-Environnement, Université Joseph Fourier, Grenoble Cedex 9, France

Jean-Luc Charlou Métallogénie, Géosciences Marines, Centre Bretagne, Ifremer, Plouzané, France

Alain Cheilletz École nationale supérieure de géologie deNancy, Vandœuvre-lès-Nancy, France

Jean-Pierre Donval Métallogénie, Géosciences Marines, Centre Bretagne, Ifremer, Plouzané, France

Yves Fouquet Centre Bretagne, Laboratoire Géochimie Métallogénie, Ifremer, Plouzané, France

Yves Fouquet Centre Bretagne, Géosciences marines, Ifremer, Plouzané, France

Joëlle Galéron Centre Bretagne, Environnement profond, Ifremer, Plouzané, France

Élie Jarmache Secrétariat général de la mer, Paris, France

Denis Lacroix Station de Sète, Ifremer, Sète cedex, France

Marcia Maia Institut universitaire européen de la mer (IUEM), Université de Bretagne occidentale, Plouzané, France

Bruno Martel-Jantin Bureau de recherches géologiques et minières (BRGM), Paris, France

Manuel Munoz Observatoire Terre-Univers-Environnement,Université Joseph Fourier, Grenoble Cedex 9, France

Antoine Valéry French Institute of International Legal Experts, Paris, France

Olivier Vidal Observatoire Terre-Univers-Environnement, Université Joseph Fourier, Grenoble Cedex 9, France

Acronyms

ANR	French National Research Agency
BRGM	French Bureau of Geological and Mining Research
CEA	French Atomic Energy Commission
CNRS	French National Centre for Scientific Research
COMES	French Committee for Strategic Metals
COMRA	China Ocean Mineral Resources Research and Development Association
DSMR	Deep-Sea Mineral Resources
EEZ	Exclusive Economic Zone
EPIC	French Public Industrial and Commercial Establishment
EPST	French Public Scientific and Technical Research Establishment
EU	European Union
GERPA	French Prospective Resources Study Group
Ifremer	French Research Institute for Exploration of the Sea
INSU	French National Institute for Earth Sciences and Astronomy
ISA	International Seabed Authority
LTC	Legal and Technical Commission (of the ISA)
MPA	Marine Protected Area
NGO	Non-Governmental Organisation
OSU	Earth Science and Astronomy Observatory
PPP	Public/Private Partnership
RTRA	Thematic Advanced Research Network
UBO	University of Western Brittany
UMR	Joint Research Unit
UNCLOS	United Nations Convention on the Law of the Sea

Introduction

Recent analyses, notably in France and Europe, show that the European states are liable to be faced with changing global raw materials markets. These markets are already highly dependent on imports of metal minerals and so-called “high-tech” metals such as cobalt, platinum, rare earth elements and titanium.

This means that supply sources must be diversified, thus opening up a new field for future exploration and exploitation, which in some cases have already begun, of deep-sea mineral resources (DSMR). Furthermore, national strategies on such marine resources are being developed in countries other than France (China, India, Brazil, Russia, Germany…). There is therefore real convergence between national and European, or even global, approaches, as shown by discussions already in progress within the United Nations and the G8. It thus appears necessary to define a national strategy in this field, based on a long term vision, in particular in legal terms, given the fact that mining licenses and permits are granted to States by the International Seabed Authority (ISA).

In September 2009, the President of Ifremer initiated a foresight study on deep-sea mineral resources by 2030, with twenty-three partners representing the sector’s main players: ministries, industry, research institutes, universities, specialised agencies and the European Commission. The aim was to identify the challenges and potential of these resources, the conditions required for their exploitation and their medium term development in order to define and set up appropriate strategic partnerships and programmes. Four types of potential resources were selected: hydrothermal sulphides, cobalt- and platinum-rich crusts, polymetallic nodules and natural hydrogen.

Ifremer has been conducting research in this field for many years and has acquired experience and skills, in particular in terms of marine metallogeny, international cooperation with other partner or potential competitor countries (Russia, Brazil…), marine equipment (vessels and subsea technology), oil industry partnerships (impact studies, biodiversity, deep-sea ecosystems) and technological research into deposit exploration and exploitation procedures.

Furthermore, mineral resources are listed as one of the ten priorities in Ifremer’s strategic plan for 2020, as well as in the objectives of its 2009–2013 contract. The French environment and research ministries expressed their interest in a study on deep-sea mineral resources and their willingness to support such an initiative in various forms. A French Government communication at the Council of Ministers on 27th April 2010 highlights the importance of strategic metals for France, the need to improve scientific knowledge on land and at sea, and the need for related technological developments.

Part I
Study Summary

Chapter 1
Study Summary

Yves Fouquet and Denis Lacroix

Challenges

Today humanity crucially needs to discover new natural resources, due to world population growth and high economic demand from the major emerging countries (China, India…). Just like energy resources, mineral resources constitute one of the key elements of the development of industrial economies. Due to soaring prices of raw materials and metals, together with the need to diversify supply sources, new deposits are being sought both on land and at sea. The ocean covers 71 % of the Earth's surface (including 60 % over 2,000 m deep), yet this vast area remains poorly known. Its wealth could become vital for global needs in terms of energy and raw materials. For a few years now, supply tensions have no longer only concerned base metals (copper, zinc, lead…), but also rare metals (rare earths, indium, platinum group metals (PGMs), gallium…) sometimes referred to as critical or strategic metals due to their expanding use in new technologies (electronics, military applications, clean energies…).

Scientific deep-sea exploration over the past 30 years has identified several geological and geochemical processes resulting in metal accumulation (polymetallic nodules, cobalt-rich crusts and hydrothermal sulphides) and the genesis of original potential energy resources (methane hydrates, hydrogen). These discoveries open up new prospects for exploration and identification of ocean mineral and energy resources. These potential resources are related to active submarine processes, which have no land-based equivalent on the continental crust.

For the past few years, the mining industry has been taking an interest in submarine hydrothermal mineral deposits. Exploration approvals have been granted for

Y. Fouquet (✉)
Centre Bretagne, Laboratoire Géochimie Métallogénie, Ifremer,
CS 10070, 29280, Plouzané, France
e-mail: yves.fouquet@ifremer.fr

D. Lacroix
Station de Sète, Ifremer, avenue Jean Monnet,
CS 30171, 34203, Sète cedex, France
e-mail: denis.lacroix@ifremer.fr

Y. Fouquet, D. Lacroix (eds.), *Deep Marine Mineral Resources*,
DOI 10.1007/978-94-017-8563-1_1, © Éditions Quæ 2014

many hydrothermal fields in the Western Pacific to Nautilus Minerals (230,000 km^2) and Neptune Minerals (264,000 km^2). Nautilus are preparing to exploit hydrothermal deposits in Papua New Guinea, which will constitute the first mineral mining operation at a depth of 1,800 m. French oil industry engineering company Technip is at the forefront alongside Nautilus and Neptune, providing the equipment required for the deep-sea mining of sulphide ore.

These recent breakthroughs raise geopolitical issues. Access to mineral raw materials gives rise to increasingly visible international competition. What is, or will be, France and Europe's strategy to determine its position in this field, secure its supplies and develop specialised technologies. What types of cooperation should be prioritised in order to be well placed in 20 years' time? How is European industry placed in this field? A specific commitment from France will be required to conduct investigations, over and above the current mapping effort. Such investigations will enable potential mineral and energy resources to be located and inventoried in the extension of the country's national territory which makes up the world's second largest exclusive economic zone (EEZ). Finally, to assess the wealth of these deposits, with a view to exploiting them, environmental studies involving geologists, chemists and biologists will be required.

Faced with rapidly evolving demand for mineral raw materials and growing interest from industry, the ISA voted in a text in 2010 which governs the exploration of sulphides in international waters. China immediately submitted an application for exploration of hydrothermal mineral deposits in the Indian Ocean. There is a risk of scientific research being restricting to certain areas. France's position is all the more justified as it has 30 years of expertise in this field.

On an international level, Russia supports a major exploration and inventory programme for hydrothermal mineral resources along the Mid-Atlantic Ridge, for which it has recently submitted an exploration application to the ISA. Japan, the United States and Germany include metals in their medium term priorities. Finally, China, India and South Korea are launching ambitious exploration programmes based on access to deep-sea resources. All these initiatives draw upon long term strategies including, in order, strong political will, development of technological skills and access to scientific knowledge and deep-sea resources as a factor of economic independence.

A Changing Societal Context

Like oil, mineral resources are generally non-renewable; their formation is slower than their consumption rate. This is therefore a limited resource that can be exhausted, with serious consequences for the environment. Known reserves of many metals are expected to be exhausted within 10–50 years, on the basis of current consumption rates.

The short term vision of mineral availability at the Earth's surface is generally conceived according to the needs of developed countries. Current resources would not allow all the planet's inhabitants to use metals to the same extent as the current average consumption of rich countries (this would require quantities three times higher). The internal production of rapidly growing countries, such as China and India, will not be able to meet their needs. The foreseeable rise in demand, related to world population growth and the rising standard of living in developing countries, considerably reduces the estimated lifespan of metal reserves. The problem becomes acute if we look 30 years ahead. Exploration is therefore justified in order to identify new reserves.

The needs generated by the constant rise in the standard of living in many large countries imply a 7–9 % growth rate for several decades, and the maintenance of around a 3 % growth rate in wealthy countries. This growth requires increased consumption of energy and mineral resources. This leads to serious problems in terms of resource availability, whose limits are now better known, and raises the question of sustainable management of the world's development.

Developed countries are increasingly dependent on external sources of energy and mineral resources. They represent 20 % of the world's population, but consume 80 % of its resources. Consumption per capita is 15 to 20 times higher than that of poor countries. If resources were to be equally shared between all the countries of the globe, developed countries would be allocated less than a quarter of their current consumption. This situation does not make for balance. Furthermore, in the future, countries like India and China will place an increasing strain on access to resources. China's annual zinc consumption, for instance, increased from 0.66 kg per capita in 1996 to 1.07 kg in 2000, then to 3 kg in 2010. Problems in supply are therefore unavoidable in the medium term. This issue was raised as early as 1972 in the conclusions of the Club of Rome report; even although consumption curves have changed, the trend presented for the next 30 years remains the same.

Europe is increasingly dependent on external metal supplies. Such a situation entails high risks of shortages in the event of market tensions. During the past 5 years, the prices of certain metals have risen by over 300 % (Fig. 1.1). After a short-lived drop during the 2008 crisis, these prices are constantly rising once again.

Due to resource depletion, ores of declining grade are being mined at increasing depths. However, ore concentration limits cannot be lowered below a certain level due to the increase in the energy required for their extraction and a higher environmental impact.

Metal supplies during the coming decades will therefore involve a sustainable component (recycling) in the metal lifecycle, as well as the discovery of new mineable deposits in areas yet subject to little exploration. The vast ocean area in which scientific exploration has identified mineral resources therefore constitutes a potential worthy of study.

Ocean Challenges

Over the next 30 years, humanity is set to take an increasing interest in the deep-sea environment, from a scientific point of view, but also from economic, ecological and educational perspectives. The need for a long term strategy is becoming urgent;

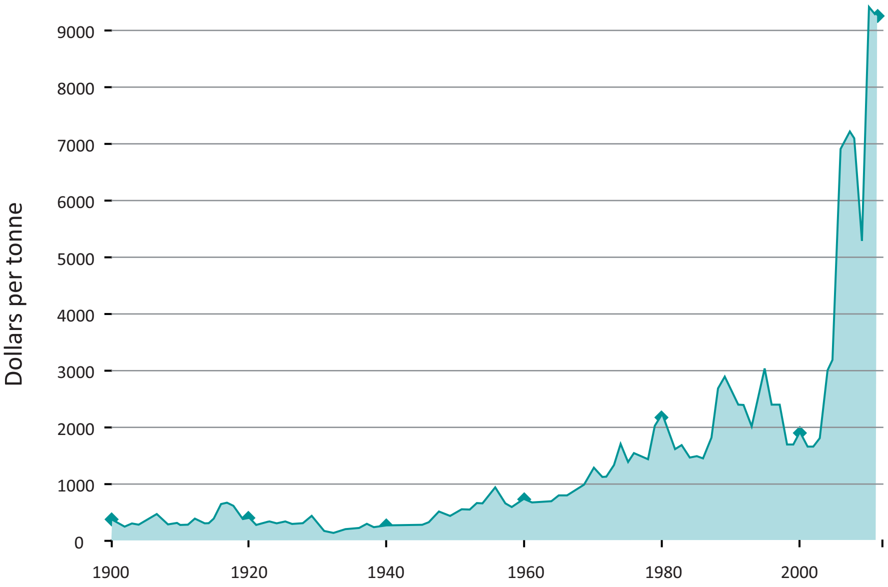


Fig. 1.1 Evolution of copper prices during the twentieth century. (Source: United States Geological Survey)

such a strategy will be determined by geopolitical factors and global economic challenges. The aim, for both France and Europe, is to define specific policies to prevent ourselves from being outrun. Europe must define its cooperation strategy with the world's other major hubs in order to preserve its position in terms of science and training, to derive technological, economic and ecological benefit and to ensure its independence.

Thanks to sustained research efforts over the past 30 years and to the availability of increasingly high-performance investigation and sampling equipment, France has acquired recognised expertise and is well placed to determine the geological processes resulting in the accumulation of the most valuable mineral deposits in the world's oceans. Over and above mining issues, there are many challenges relating to deep-sea mineral resources.

Scientific Challenges

Knowledge of the ocean floor through scientific exploration is crucial in order to identify the richest mineral areas and to understand metal transfer and concentration processes. This exploration also provides better knowledge of the biodiversity and functioning of deep-sea ecosystems.

Geopolitical and Economic Challenges

These challenges are fundamental for access, during the coming decades, to mineral raw materials (base metals and rare metals) on a global scale. It is important to place this within the context of competition, on land and at sea, with rapidly growing countries. Many challenges are associated with the promotion of the French EEZ and its extension via the Extraplac programme, as highlighted by the French Ministry of Higher Education and Research's 2010 report on the territorial strategy for overseas territories (Stratom).

Technological Challenges

As this industry is new, the countries and industrial firms that manage to anticipate and master exploration and exploitation technologies will be able to draw the benefit of their know-how on a global scale. This position is being grasped, in France, by the firm Technip, by defining a long term strategy in this field.

Environmental Challenges

Based on the observation that there a very few operable land-based ore mines on the earth's surface, deep-sea exploration to search for mineral resources will provide knowledge of vast areas that will never be mined. This exploration effort should boost knowledge of biodiversity and enable protection areas to be defined, in the form of reference areas or marine protected areas (MPAs), in order to guarantee the right balance between preservation and exploitation. The data acquired will also be fundamental for mining impact studies.

Legal Challenges

The ISA, which comes under the UN, has introduced legislation and manages the approvals granted for nodule areas in the North Pacific. The legal texts relating to polymetallic sulphides were validated in May 2010. The regulations on crusts are under preparation. Discussions could result in legislation restricting scientific research to certain limited areas. France must take a stand on this issue to preserve its headstart in terms of knowledge of deep-sea mineral resources and biodiversity.

Framework

Within this general background, the pivotal question of the study is that of evaluating the potential of the main deep-sea mineral resources (metal ores and natural hydrogen) that represent a strategic goal for France and the European Union for 2030.

This study aims to answer three main questions on these resources by 2030:

- What scientific and technological knowledge is required for their discovery and exploitation?
- What socio-economic conditions are liable to make their exploitation competitive?
- What environmental impacts of their exploitation can be foreseen?

During the first Steering Committee meeting on 30th September 2009, at Ifremer headquarters, the 24 organisations represented—companies, ministries, universities and specialised research institutes—defined the study's characteristics. These characteristics can be summarised as follows:

- Time frame: 2030.
- Scope: the world, with a particular focus on France within Europe.
- Technologies: all marine technologies, excluding fossil fuels.
- Method: methods, trends, impacts and scenarios.
- Time allocated: 1 year.

Methodology

In terms of methodology, this analysis drew upon the representation of the studied system (global environment, review of current scientific knowledge, sectors, challenges for stakeholders) before exploring possible evolutions of major variables, followed by the conditions required to harness the potential of these resources. It was therefore possible to identify the dynamics relating to the main sectors and draw lessons in order to define action proposals, including a national research and development programme.

This work mobilised around 30 experts over a ten-month period, half of which worked within a permanent Working Group. The methodology was defined by Gerpa, a firm specialised in industry studies. The method consisted in cross-analysing the evolution of 17 variables up to 2030 according to 3 contrasting macro-scenarios whose main determinants were as follows: markets, international trade, legal status of international waters, national and/or multinational interests and critical mineral supply security, impacts on the deep-sea environment, stakeholder involvement and societal perception.

The ten working meetings, as well as the three Steering Committee meetings, were planned over 10 months, which facilitated the continuity of efforts and progress monitoring. These meetings were held between 30th September 2009 (first Steering Committee meeting) and 7th July 2010 (last Steering Committee meeting). The Working Group also heard 14 experts to improve its knowledge of the subjects studied.

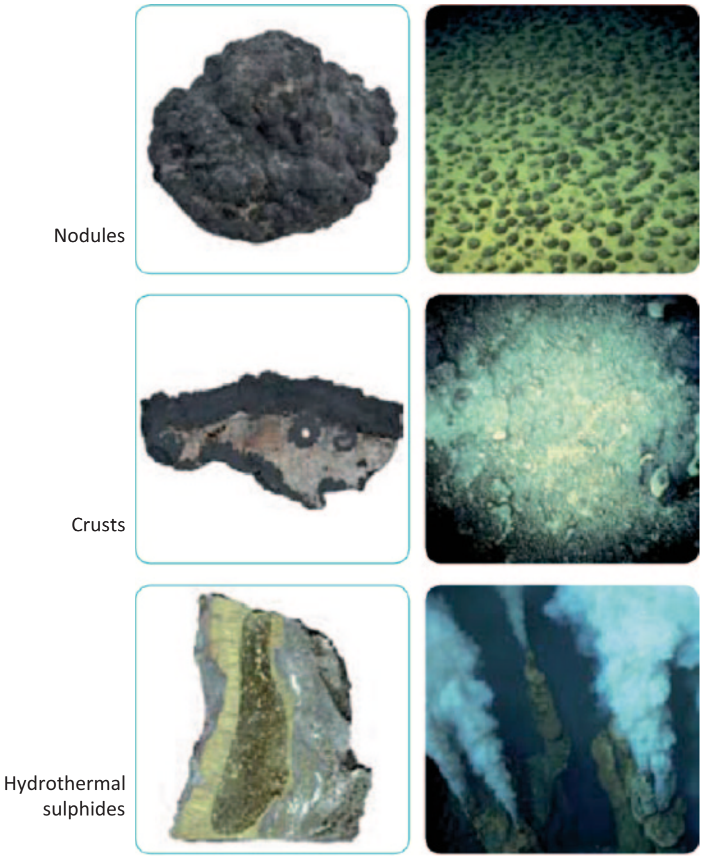


Fig. 1.2 Types of deep-sea mineral deposits

Gerpa put forward a five-stage work method: (1) define the subject, time frame and objectives, (2) identify the key variables and their relationships, (3) explore the possible evolutions of the key variables (sets of hypotheses), (4) build scenarios exploring the context and sector, (5) identify the challenges for each scenario and explore the consequences in terms of research and development for technologies and in terms of actions for the partners concerned.

In the final phase, the group restructured the results and their presentation in order to facilitate their operational use.

During the framework definition phase, four types of sites and their associated resources were selected (cf. Fig. 1.2): cobalt-rich and platinum-rich crusts, hydrothermal sulphides, polymetallic nodules and natural hydrogen production sites.

The group conducted a wider study on the mining potential of these sites by considering four types of interest: scientific, economic, strategic (supply security) and heritage (long term resources).

Cross-Cutting Challenges by Metal Type

The main metals liable to be extracted from the deep-sea environment are of different types.

Type A comprises base metals that are subject to probable economic tension (zinc, copper, manganese, cobalt, nickel, lead, barium, silver and precious metals with high heritage value: gold).

Type B is composed of a few critical metals with high technological potential and major supply risks (indium, germanium, cadmium, antimony, mercury—linked to zinc—and selenium, molybdenum, bismuth—linked to copper—on sites rich in hydrothermal sulphides, rare earths in crusts and nodules). Platinum and platinum group metals (on crust sites, with uncertainties over the risks of substitution in uses, as 200 years of possible consumption remain based on current supplies) also belong to this category. Another resource is natural hydrogen found in hydrothermal fluids of sulphide chimneys on hydrothermal sites associated with mantle rock.

Hydrothermal Sulphides: Relative Certainties and Uncertainties

Submarine hydrothermal activity is a consequence of plate tectonics and volcanic activity. These processes generate the oceanic crust at divergent boundaries that form the 60,000 km of mid-ocean ridges. The presence of heat and faults promotes the circulation of fluids in the oceanic crust. This hydrothermal activity is an important metal concentration mechanism, causing metals to accumulate in the form of sulphide deposits (Fig. 1.3). Hydrothermal sulphide deposits result from the circulation of seawater through the oceanic crust under the effect of high thermal gradients. They are found on all submarine structures of volcanic origin.

According to their location, they show great diversity in their physical and geological characteristics and the types of metals that can be mined. These differences are controlled by physical processes (temperature and depth for instance) and, to a greater extent, by the type of rocks through which the hydrothermal fluids circulate (various volcanic rocks, mantle rocks, sediments). This type of ore is well known in fossil deposits mined on land and previously formed below the sea. A small proportion of the copper, zinc, silver and gold mined on land is produced from this type of deposit, some of which also contain lead, cobalt and barium.

The first hydrothermal mineral deposits associated with hot brine (70 °C) were observed in 1962 in the Red Sea. The first black smokers (350 °C) were discovered on the East Pacific Rise in 1978, at a depth of nearly 3,000 m. After 30 years of exploration in all the world's oceans, the discovery of almost 150 hydrothermal sites (Fig. 1.4) shows the importance of extraction, transport and concentration processes for metals associated with submarine volcanic activity. Sulphide mineral deposits are now known to exist at depths of between 800 and 4,100 m. Hydrothermal fields have been identified in the main geodynamic contexts (slow- and fast-spreading ridges, back-arc basins, island arcs) and on various substrata (basalt, andesite, dacite, sediment, ultramafic mantle rock).

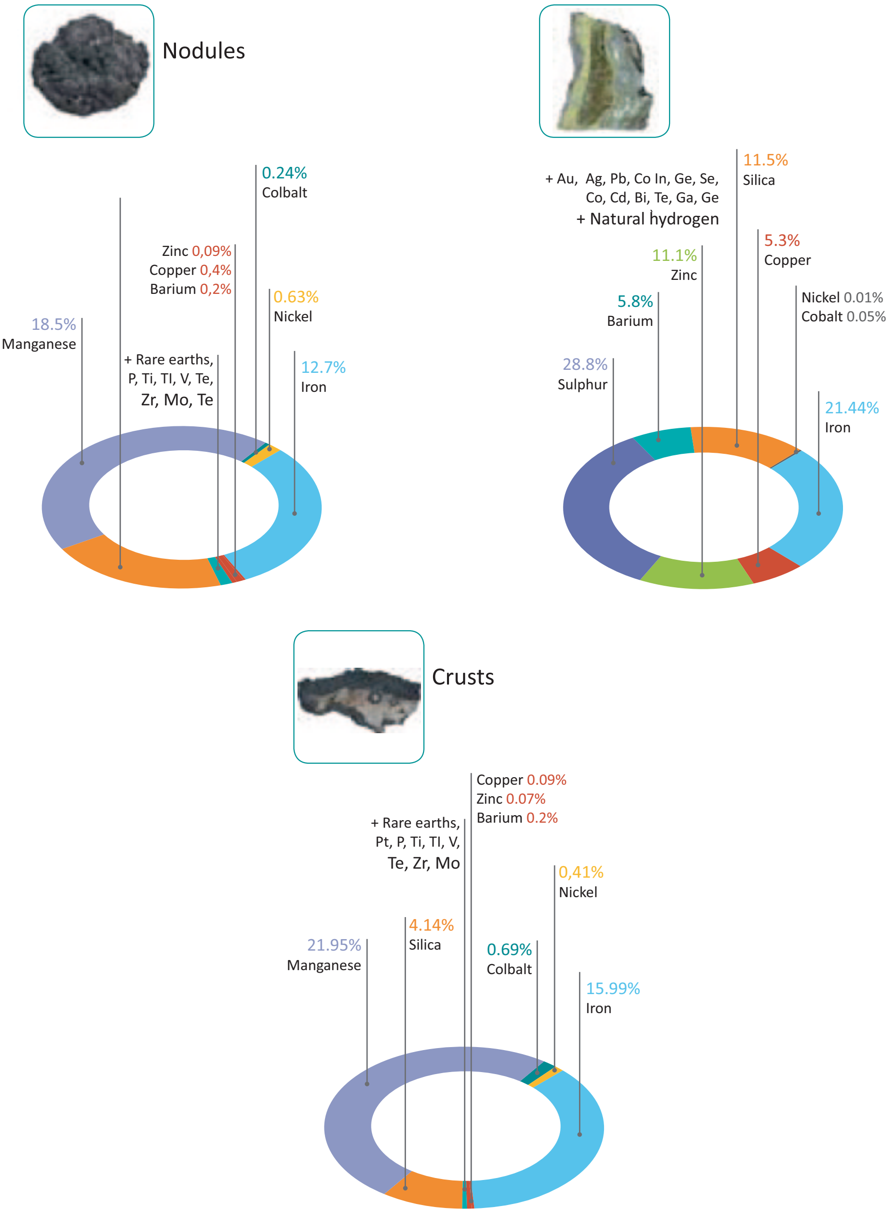


Fig. 1.3 Concentrations (% weight) of major elements in deep-water mineral deposits

Hydrothermal sulphides are characterised by high base metal contents in relation to crusts and nodules. Submarine hydrothermal mineral deposits have been studied by submersible and by dredging. These two techniques can be used to take samples, mainly at the surface. Chemical and mineral zones according to vertical depth can be

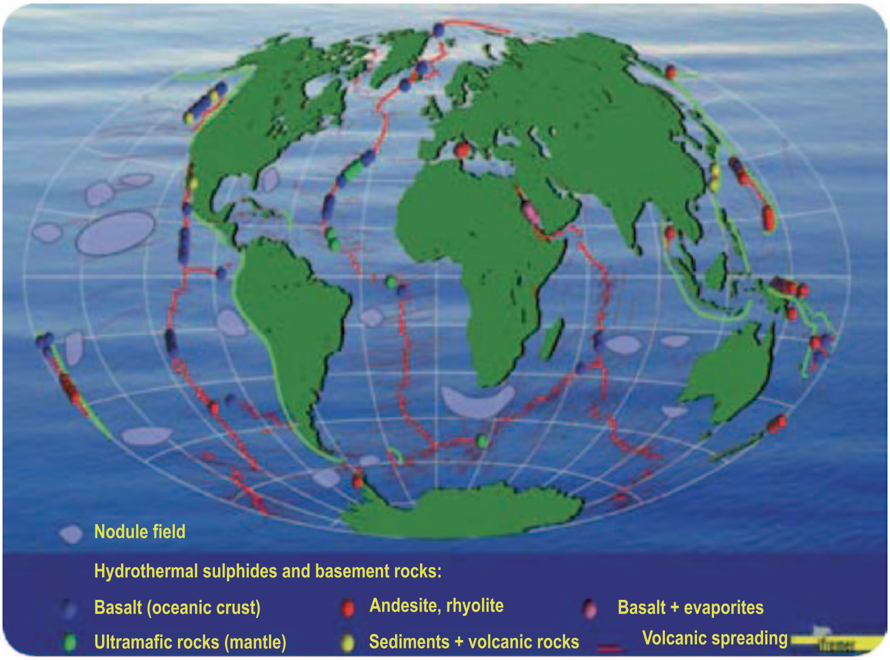
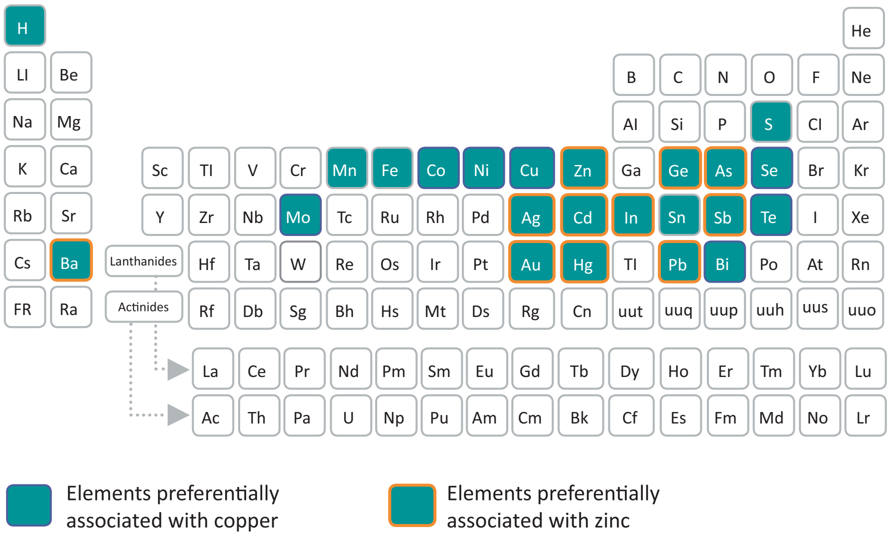


Fig. 1.4 Location of hydrothermal sites and nodule fields around the globe

studied by drilling. Samples show that the surface of most deposits is rich in copper and zinc, together representing over 10 % for more than 65 % of sites (values based on the study of 75 sites and 3,300 samples). These surface data suggest that submarine hydrothermal mineral deposits could be as rich as their land-based counterparts. With the exception of the specific case of metal-rich sediments in the Red Sea, these are massive ore deposits which generate little waste. Due to their location on the seabed, mining does not require tunnels to be dug as is the case on land. Furthermore, equipment installed on vessels can easily be relocated. These technical elements should help to minimise costs and reduce the environmental impact of mining.

Other than copper and zinc, most sites are rich in silver and often gold. Some specific sites in the Atlantic associated with mantle rocks show high cobalt contents. Several rare elements are found alongside the main metals. Copper ore deposits, characterised by their formation at temperatures of over 300°C, may also be rich in selenium, cobalt, nickel, molybdenum, tellurium, bismuth and gold. Zinc ore deposits, formed at between 100 and 250 °C, are often rich in cadmium, lead, arsenic, antimony, germanium, indium and barium (Fig. 1.5).

While site formation conditions are well enough known, the inventory of sites remains largely incomplete (with several 100 sites believed to exist). Exploration technologies can only locate active sites, whereas inactive sites need to be searched for more systematically and can only, based on current technologies, be located by operations close to the bottom.



The affinities of minor elements with copper or zinc are specified.

Fig. 1.5 Metals present in hydrothermal sulphide deposits

In the deposits studied, the following characteristics were observed:

- Variability in ore composition and concentration; many related metals (e.g. Zn/Ge) and natural hydrogen, knowledge to be improved for critical metals.
- Variability in deposit size and composition (formation in bunches): from 0.5 to 100 million t.
- Major biological wealth in active areas, but "pinhead" knowledge. Requires improvement for inactive areas.
- Natural hydrogen: scientific study for the quantification and knowledge of geochemical processes.

Elements on Potential Exploitation

The gross value of submarine sulphide deposits is not yet well known, due to a lack of sufficiently studied reference cases which would provide an initial idea of the average value of the resource. Based on metal prices on 18th October 2010, the average value of known resources in the Solwara I deposit was US $ 834 per tonne and that of the Atlantis II Deep in the Red Sea was US $ 122 per tonne. It is possible that deposits with higher values may be identified subsequently.

Mining technologies are known for each segment. Extraction processes are under development and validation. The storage, logistics and processing of the ore are currently being studied. The current Nautilus project (Papua New Guinea EEZ) should provide many lessons. On a global scale, technology in this field is being led by France, with Technip at the head (pilot project). The extraction cost appears to be roughly comparable to extraction costs for underground mines ($ 90 per tonne) with a predicted development time of 2–5 years.

Stakeholder Involvement

For many years, stakeholders have been involved in a wide range of actions: publications by active scientific communities, NGO mobilisation on site protection, emergence of economic players (Nautilus, Neptune), rise of technological players (Technip), emergence of political criteria (4 critical metals out of the 14 identified by the European Commission), expansion of legal scope (allocation of licenses in international waters and EEZ management).

The most active countries in exploration in international waters are the following: China, Korea, Russia and India. The legal framework is the ISA regulation adopted in May 2010. Applications have been submitted by China (May 2010) and Russia (December 2010).

Cobalt-Rich and Platinum-Rich Crusts: Relative Certainties and Uncertainties

Ferromanganese oxide crusts have been identified in all the oceans, in environments in which the combination of currents and low sedimentation rates have prevented sediment deposit for millions of years. In general, they are associated with intraplate submarine elevations, isolated seamounts and volcanic chains. They vary in thickness from a few centimetres to 25 cm and cover surface areas of several square kilometres. They are generally deposited on indurated substrata (volcanoes, former underwater atolls) at depths ranging from 400 to 4,000 m. Estimations indicate that the total surface area covered by crusts is around 6.35 million km^2, i.e. 1.7 % of the ocean surface.

The first systematic investigations began in 1981 in the Central Pacific Ocean. Over the past 20 years, many countries have taken an interest in these potential resources: Japan, the United States, Russia, Germany, France, Korea, the United Kingdom, Brazil and China. Few submarine volcanoes (out of an estimated 50,000) have been studied in this ocean. Cobalt- and platinum-rich deposits have the greatest economic potential. All of these deposits are located in the Pacific, especially in the EEZ of French Polynesia. These deposits appear on the external edges of submarine plateaus (like in the Tuamotu Islands) and on volcanoes, at depths ranging from 800 to 2,500 m.

Like nodules, crusts are mainly composed of iron and manganese oxides. They are on average three times higher in cobalt and often have high platinum concentrations (Fig. 1.6). The highest concentrations (maximum of 1.8 % cobalt and 3.5 g per tonne of platinum) are located in Polynesia, between 1,500 and 2,000 m deep. The “metal content” value is 2–3 times higher than that of laterite mined on land where the content does not exceed 0.4 %. These crusts could constitute the first cobalt ore, as this metal is to date a by-product of other mining processes. On certain sites,

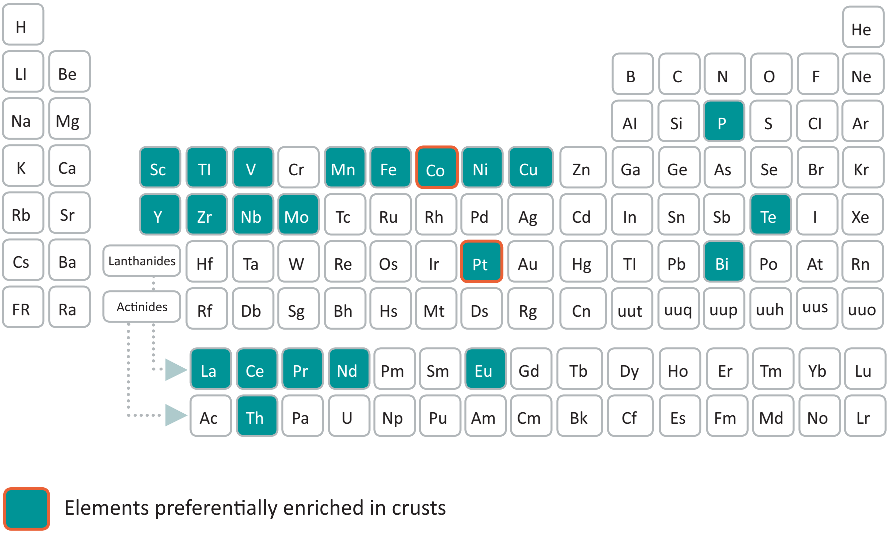


Fig. 1.6 Elements accumulated in nodules and hydrogenetic crusts

platinum could prove to be an interesting by-product. Several minor elements such as rare earths (yttrium, lanthanum, cerium), titanium, thallium, zirconium, tellurium and molybdenum can be found in high concentrations. Rare earths, platinum and cobalt tend to be more concentrated in crusts than nodules (ratio of 1–10 for rare earths).

Knowledge of the concentration process and of the location of the richest areas in rare elements is partial and improved understanding of the geological and chemical parameters governing the formation of the richest accumulations is required.

From a scientific point of view, efforts remain necessary to more fully understand the rules of distribution, variability in thickness and composition and formation processes. From an economic point of view, much work remains to be done to assess deposits, determine the richest and most favourable areas for mining: smooth, flat areas to allow collection without excess dilution. Such cobalt-rich areas are known in the Tuamotu Islands where crusts form a flat, continuous surface on indurated sediment formations.

The location of sites and their intrinsic mineral wealth are roughly known. Detailed mapping remains to be performed, as does the inventory, even approximate, of the biodiversity specific to this type of formation.

Elements on Potential Exploitation

The gross value of ore is relatively high (platinum and cobalt), ranging from $ 500 to 1,300 per tonne (2010). Mining technologies and the related costs are uncertain for several reasons: no demonstrator, variability in crust thickness (2 cm, 20 cm), poor knowledge of seabed, extraction difficulties… resulting in a predicted development time of 10–20 years.

Stakeholder Involvement

Stakeholder involvement concerns areas mainly located in EEZs with scientific investment by the following countries: Japan, United States, Korea, France, China, Brazil (international waters). There is no industry and are few publications. The current legal framework is on a national scale. For international waters, this framework is currently being defined by ISA.

Nodules: Relative Certainties and Uncertainties

Polymetallic nodules are known in all the oceans, at all latitudes, at depths of over 4,000 m and in areas characterised by a low sedimentation rate and radiolarian ooze. In particular, these areas allow carbonates to dissolve, due to greater acidity of deep waters, caused by greater solubility of CO_2 with pressure.

Metal abundance and wealth on the seabed vary greatly. From 1973, fields with a high density of nodules were found along an east-west belt in the North Pacific (Clarion-Clipperton Zone). Nodules form dark-coloured balls, 5–10 cm in diameter, containing around 40 % water. They are mainly composed of manganese and iron hydroxides. The most crystallised layers are the richest in nickel and copper, which do not form specific minerals, but are incorporated in the crystalline networks of manganese and iron oxides.

The base metals contained in nodules are iron (7–23 %), manganese (7–26 %), copper (290–10,200 ppm), nickel (2,600–12,800 ppm) and cobalt (2,400–8,000 ppm). The Clarion-Clipperton Zone presents high concentrations of copper (0.82 %), nickel (1.28 %) and manganese (25.40 %), and many mining licenses have been allocated for this area. These are the metals that have been considered in economic estimations. Copper is found in concentrations on average double those of the major mines in the Andes (0.5 %). Nodules can have high levels of rare elements such as cerium (0.1 %). Other elements such as molybdenum, tellurium, vanadium, zirconium and thallium can be found at concentrations of several 100 gm/t.

Nodules can also be considered as strategic reserves for base metals and for certain rare metals. Several countries, including the United States and Germany, have undertaken to resume analyses of their collections of nodules using modern analytical methods in order to determine the variability in the composition of minor elements and in particular rare earths.

Recent estimations for the Clarion-Clipperton Zone show that, for a surface area of around 9 million km^2 (i.e. 15 % of the Pacific floor at a depth of between 4,000 and 5,000 m), the weight of nodules is 34 times 10^9 t, i.e. 7.5 billion t of manganese, 340 million t of nickel, 275 million t of copper and 78 million t of cobalt. Nodules also contain certain trace metals, which are currently generating growing interest.

Their mining potential has been highlighted since the 1950s due to nickel contents greater than or equal to those of laterite deposits, copper contents greater than or equal to those of major land-based porphyry copper deposits (0.5 % copper) and cobalt contents similar to those of land-based deposits. The "metal content" value (copper + nickel + cobalt = 2.4 %, cf. Fig. 1.3) of nodules is equivalent to that of land-based deposits. Growing awareness of the potential economic importance of nodules caused President Johnson in 1966 to call for the seabed to be declared common heritage of mankind. This proposal was made into a resolution in 1970 by the United Nations General Assembly.

As copper resources, nodules represent around 10 % of continental reserves and underwent many investigations in the 1970s and1980s. These investigations did not lead to their exploitation for various reasons: water depth of over 4,000 m, poor estimation of the resource, high cost of metal processing, political issues related to the law of the sea and a slump in metal prices. Precise evaluation of their potential requires high resolution maps to be produced, the formation processes for the richest nodules to be understood and the biodiversity and functioning of related ecosystems to be well known, in order to minimise environmental impact. With this in mind, France has obtained two mining licenses in the North Pacific.

The sites and mineral compositions have been known for base metals since the late 1980s. Studies on biodiversity aspects are in progress. Collections must also be resumed to improve knowledge of rare metal concentrations.

Elements on Potential Exploitation

The gross value of the ore varies from low to average levels, i.e. from $ 200 to 700 per tonne, depending on the year. Mining technologies are still uncertain, as there is currently no pilot, even although there are no technological barriers. Yet the extraction depth is high (4,000 m). Consequently, the predicted development time is 10–20 years.

Stakeholder Involvement

Stakeholder involvement revolves around the issue of access to nickel, especially for China, hence the recent renewed scientific and technological interest in nodules, as well as debates on aspects relating to protection of the environment and biodiversity. Germany and the United States are also taking an interest in knowledge of rare metal concentrations. The legal framework in international waters is that of the ISA. Seven exploration licenses have been approved for international waters, including one French contract valid until 2016.

Natural Hydrogen

Hydrogen stored in the ore of oceanic rocks plays a very important role in redox reactions which occur during interactions between seawater and rock through hydrothermal circulation. Hydrothermal circulation is possible in fractured environments and is triggered by the magmatic heat source present in the ocean depths.

Hydrogen has a high potential to combine with most elements of the periodic table at high pressure and high temperature, forming metal hydrides, unstable in the presence of water. Thanks to hydrogen, a large number of elements, transition metals, lanthanoids and actinoids, of recognised metallogenic interest (titanium, vanadium, chromium, cobalt, molybdenum, tungsten, uranium, thorium, gold…) can be transported in the mantle.

In hydrothermal circulation, hydrogen combined with sulphur (H_2S) interacts with the metals extracted from the rock to precipitate metal sulphides, forming chimneys and hydrothermal mineral deposits along mid-ocean ridges and in back-arc basins.

Hydrogen is also generated in large quantities during serpentinization of mantle peridotites along slow- and ultraslow-spreading ridges and in subduction zones. We now know that hydrogen and methane production are closely linked to ultramafic rock outcrops on the ocean floor and on the walls of slow-spreading ridges. Hydrogen is produced abiotically at low temperatures (<20 °C) by diffusion and degassing of "inactive" serpentinized seamounts or at high temperatures (350 °C) at "active" hydrothermal chimneys.

Since 1995, seven active high (>350 °C) or moderate (~90 °C) temperature sites have been discovered along the Mid-Atlantic Ridge in the mantle domain, at depths ranging from 1,700 to 4,100 m, all producing large quantities of hydrogen. Recent work has shown that the serpentinization phenomenon with hydrogen and methane production was also present in many segments of the slow-spreading Arctic Ridge as well as the Indian Ridge.

Global hydrogen flows obtained from oceanic serpentinization are as yet poorly known. Current estimations of these flows vary between 90 and 190 billion moles per year. These very preliminary calculations should be fine-tuned by continuous, in-depth exploration of slow-spreading ridges providing "field" data, but also through experimentation and laboratory-based work, which will provide a better understanding of reaction mechanisms, enable modelling of the natural production-migration process, as well as the geochemical and thermodynamic processes implemented on a large scale.

Environmental Challenges

Deep-sea mineral and energy resources are located in highly contrasting areas of the ocean. On ocean ridges or active systems of back-arc basins, active or past hydrothermal systems are at the origin of the production of sulphides rich in metals and natural hydrogen. Crusts rich in cobalt and other metals are generally present on seamounts formed from former volcanoes, but they can also be associated with ocean ridges and plateaus. Finally, it is in abyssal plains that polymetallic nodules are found. In these areas, the highly variable environmental conditions determine the development of biological communities, which too are highly variable.

The Exuberant and Extraordinary Life Around Hydrothermal Chimneys

Discovered in the 1970s, ecosystems related to the expulsion of hydrothermal fluids are today known to host exuberant and extraordinary communities, in as far as their development is based not on photosynthesis, like almost all life on our planet, but on chemosynthesis. Micro-organisms are the founding elements of these systems which comprise hundreds of species of invertebrates, often large in size and mostly new to science.

Knowledge of these environments and the life developing there is still quite incomplete. Scientific progress in the understanding of how these ecosystems work and how organisms adapt to the strong constraints of the environment leads us to believe that many scientific discoveries are still to come. It is therefore crucial to preserve these unique ecosystems.

Beyond active hydrothermal sites, very few data exist on the nature and distribution of fauna associated with ocean ridges and volcanic back-arc systems. Nevertheless, the complexity of their topography, its influence on hydrodynamics as well as the heterogeneity of hard and soft substrates are thought to enable the coexistence of assemblages of highly diversified specific organisms, with a majority of fixed suspension feeders on rocky substrates (with, for instance, gardens of solitary corals or sponges) and mobile detritus feeders on and in soft sediment.

In these systems, the exploitation of sulphide deposits would have a direct impact on the benthic ecosystem of inactive metal deposits (destruction of the environment and living organisms) and indirect impacts related to the propagation of sediment plumes (alteration of the environment's physical and chemical characteristics for the pelagic ecosystem) and their sediments, by mechanical and chemical effects on chemosynthetic ecosystems in active areas and adjacent benthic ecosystems. This impact will depend on the exploitation technique developed. We note however the existence of a natural impact lasting several tens of thousands of years, related to the dispersion of dissolved metal elements and particles by natural plumes at active vents.

The potential exploitation of natural hydrogen produced by hydrothermal vents would have consequences mainly on the chemosynthetic ecosystem. It would directly affect the energy source at the base of the ecosystem and chemically alter the environment.

Furthermore, the elimination or restriction of the hydrothermal plume could also affect the dispersal of the larvae of organisms living in these systems, restricting gene flows between sites on a regional scale. Finally, the mechanical constraints of exploitation structures on these fragile environments are unknown.

Specificities of Seamounts

Knowledge of the biological communities associated with cobalt-rich crusts is limited. Nevertheless, recent studies have shown that these communities are comparable to those of other rocky substrates on seamounts, favourable environments sheltering these resources. These structures are generally large, with very sloping sides; their topography can be complex due to the presence of terraces, canyons, calderas or craters; hard and soft substrates coexist in different thicknesses and compositions.

This complexity, together with strong hydrodynamics and a high bathymetric gradient, greatly shapes seamount communities, known today to be home to high levels of biological diversity and biomass, also composed of fish which are already targeted by heavy fishing activity. The endemism rate of species and connectivity between populations are related to various biotic and abiotic factors, the most important being distance between seamounts, hydrodynamics and larval dispersal capacities. The direct and indirect consequences of exploiting the resources in these environments can be expected to be comparable with those of the exploitation of the above-mentioned sulphide deposits.

Sediment Fauna Diversity on Abyssal Plains

Abyssal plains conducive to the formation of polymetallic nodules are located in ocean areas characterised by a very low sedimentation rate and oligotrophic conditions (low nutrient availability) for deep-sea communities. These large stretches generally have low slopes; they may be intersected by hills or seamounts with more marked slopes, formed from rocky substrates. The vastest and richest nodule fields are located in the North-East Pacific, between the Clarion and Clipperton fracture zones at an average depth of around 5,000 m. The biological wealth of sediment environments in this zone is mainly composed of small invertebrates (tens of microns to a few millimetres) and micro-organisms. These communities are concentrated in the top few centimetres of sediment; their density and local diversity are high. Large organisms are rare in this oligotrophic environment. The structure of these communities varies within the zone, due to the heterogeneity of the habitat, generated by various factors including primary production gradients (east-west and north-south), the topography and the presence/absence of nodules on the bottom.

The exploitation of polymetallic nodules would have direct consequences (destruction of the habitat in the area exploited) and indirect consequences (redepositing of sediment plume over a wider area) on the area's ecosystems. The extent of the impact would also be exacerbated by the vulnerability of abyssal benthic populations to disturbance, due to the scarcity of the majority of species and low biological activity rates related to the oligotrophic conditions in the environment. Recolonisation and population restoration processes could take years, or even decades.

Environmental Consequences of Exploitation

Generally speaking, deep-sea mining would have various levels of impact on the environment and on biodiversity, including local destruction of habitats and related ecosystems, but also disturbance to the environment (water column and seabed) and biological diversity over a more extensive area and for a far longer period of time than the mining itself. The level of knowledge of the different potentially threatened habitats is variable, but is generally insufficient to define the necessary environment and biodiversity protection plans in case of resource exploitation. In particular, it is important to understand the natural variability of an ecosystem in order to assess the level of impact of mining activities; however information on these aspects in deep-sea environments is limited. It is therefore essential to promote research in order to more fully understand the biological diversity and dynamics of these ecosystems.

Protecting the Environment

With a view to the exploitation of deep-sea mineral resources, a general theory approach aimed at defining environmentally-friendly solutions may be discussed. During the exploration phase intended to identify, assess and inventory the resource and map deposits, the first stage involves characterising the surrounding environment on a regional scale (water column and seabed) and the biological diversity found there. In the water column, hydrodynamic, chemical and trophic parameters are the most relevant. As for the seabed, habitats—defined firstly by depth—substrates and trophic sources should be mapped, the environment specific to each habitat characterised and the related animal communities described.

Following the identification of sites for exploitation and extraction techniques, the direct and indirect consequences of mining on the environment and biodiversity must be assessed, by experimental approaches or in the natural environment, as well as the ecosystem's restoration or resilience capacity following destruction and/or disturbance. Long term monitoring of the impacted area and a natural area with the same characteristics should be carried out to distinguish the consequences of mining activities on biodiversity from the environment's natural variability. All the knowledge acquired during these various phases will build indispensable foundations for defining and setting up biodiversity protection areas.

Scenarios and Related Challenges

The analysis of deep-sea mineral resources by 2030 was divided into three stages: first, the study of exogenous and endogenous variables for six compartments of the global environment (in blue in Fig. 1.7 below), then for the intermediate context and finally for the mineral resources themselves.

System Variables

Global Framework Exogenous Variables

- Globalisation and growth.
- Crises.

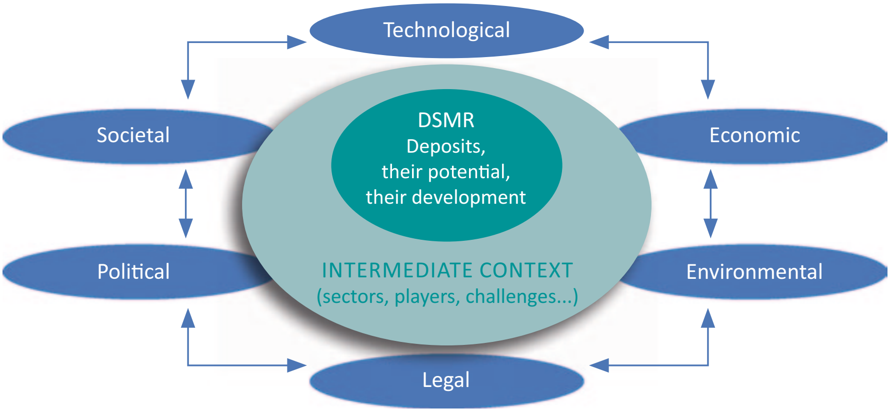


Fig. 1.7 Aspects analysed in the study of variables relating to deep-sea mineral resources. (Source: Gerpa)

- Regulation of international system.
- NGOs and environmental issues (perceptions).
- Possible pathways for the European Union.

Specific Context Exogenous Variables

- Changes in pressure on resources (economic, political).
- Place of metals in the economy, critical metals.
- Place of the sea and level of safety at sea.
- Legal aspects (ISA).
- Stakeholder involvement: States and mining industry (safety, access to technologies…).
- Supply, diversification, recovery and substitution policies.

Endogenous Variables

- Place of deep-sea mineral resources as resources.
- Stakeholders.
- Exploration and scientific collaboration.
- Deposit exploitation.
- Environmental impact of exploitation.
- Mineral processing and metallurgy.

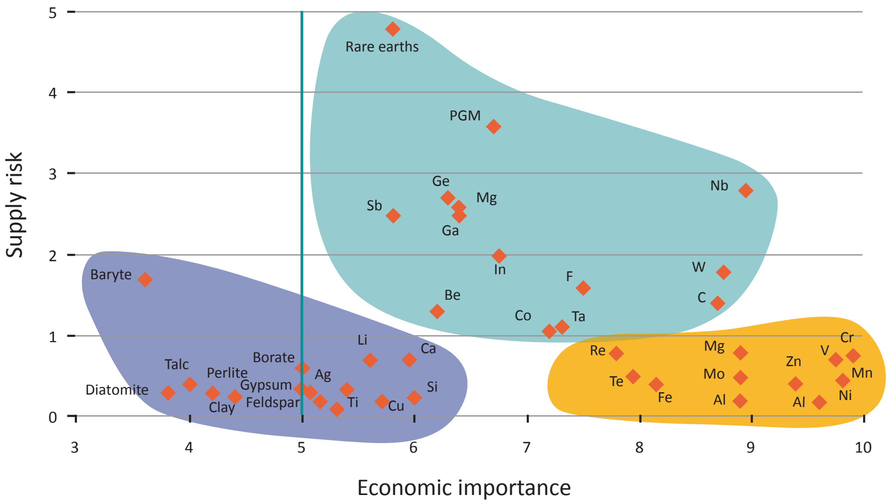


Fig. 1.8 European vision of the position of metals according to their economic importance and supply risks. (Source: European Union 2010)

Three Scenarios and Challenges for France

Collective appraisal of these variables resulted in the establishment of three contrasting scenarios, giving rise to three different types of challenges for France.

Crises and Barriers, Political Tensions

Context

Multiple geopolitical tensions in a world that has become multipolar diminish the role and influence of international organisations in general, and the ISA in particular. With a lack of consensus on international regulations on the ocean, conflicts are on the rise. They affect issues of access to knowledge and resources just as much as impact assessment or compliance with international agreements.

In this climate of growing tension, we observe reduced market fluidity, leading to the introduction of autonomous supply strategies in most major countries. States with an EEZ increase their control of potential deposits in these zones and restrict the choice of partners to the circle of their close allies. Economic importance and supply shortage risks are high, whether from a European (Fig. 1.8) or American (Fig. 1.9) perspective.

Consequently, the situation of marine mineral resources vacillates between "set-aside and harnessing".

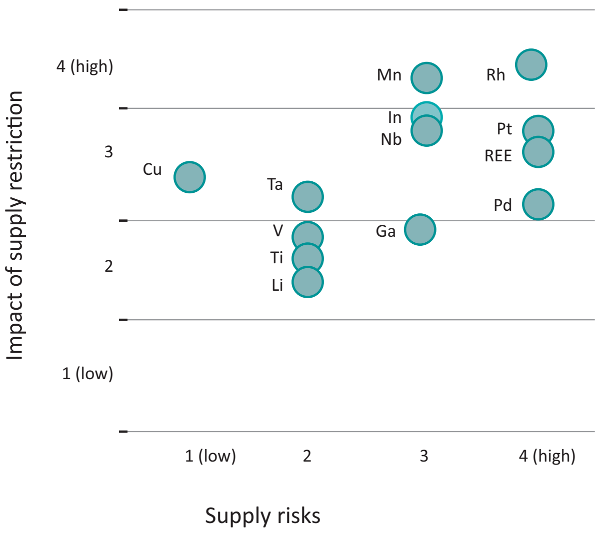


Fig. 1.9 North-American vision of the position of metals according to supply risks and the impact of a restriction. (Source: United States Geological Association (USGA) 2009)

Challenges for France

Marine mineral resources are seen first of all as a resource to be controlled within the EEZ, hence the following priorities: inventory of mineral resources in the French EEZ; definition of exploration and exploitation rules within the EEZ; seeking of agreements between States for potential deposits of strategic interest in international waters; implementation of a regional scientific and technological integration capacity, either as a European partnership or through a multilateral agreement (e.g. France, Germany and Russia).

Priority

Inventorying resources in the EEZ becomes the priority of exploration campaigns.

Cycles as Usual

Context

Regular alternation between phases of economic development and global economic recession, together with the emergence of a greater number of stakeholders in the geopolitical field, puts crises into perspective and leads to a search for reinforced cooperation between States. Economic stakeholders are in search of new sectors to maintain their competitive edge and their offer. States and industry implement supply diversification policies to preserve an operational mining sector.

Marine mineral resources thus appear as a source of potential resources and power, as their access remains restricted to a small number of advanced countries. The ISA continues to grant approvals, but has no influence over the strategies of the major States (United States, China, Russia, India, Brazil, major States of the European Union…).

Consequently, the mineral resource situation is that of a "competitive-approach economic resource".

Challenges for France

Marine mineral resources are seen as an economic resource to be developed. This implies, in the long term, developing a full-fledged sector, from exploration to exploitation.

This "competitive" approach requires good knowledge of deposits in order to select the richest deposits, hence the following priorities: implementation of public/private partnerships (PPP) for exploration and exploitation between States and private operators (French/European); management of private/public transfer; development of a mining sector (France/European Union); support to European technological economic stakeholders (pilot); sale of know-how and expertise by maintaining higher education skills.

Priority

The main objective remains to be scientific exploration campaigns to inventory resources, both in the EEZ and international waters, while preparing suitable partnerships to establish a (or several) pilot(s), then exploitation.

Global Crises

Context

The extent of recurrent crises in both the political world and the economic or environmental field (climate change) result in increased awareness of the crucial need for coordinated responses to the threats that concern all human societies, and not only certain regions or continents.

This situation restores the utility of international organisations and promotes their role. The coordination of national and regional policies becomes essential in order to boost the economy and move behaviours towards a "post-carbon" civilisation. Multinationals must fit in with these changes whether they like it or not, including in the field of critical mineral resources, and recognise their importance for green energies.

The role and powers of the ISA are growing, in particular in terms of ex-ante impact assessment for deep-sea mining projects.

Within this context, it is in industrial operators' interest to seek multiple partnerships to reduce research and development costs and secure their markets according to international standards. The deep sea therefore appears as a sort of "new resource boundary", subject to tight exploitation rules. Consequently, the marine mineral resources situation becomes that of a "global heritage reserve, liable to measured exploitation".

Challenges for France

The first challenge is that of achieving good scientific knowledge incorporating durability criteria. The second is that of shared, international exploitation, targeting critical metals (post-carbon), hence the following priorities: establishment of exemplary development and protection solutions (resilience, marine protected areas…) for French operations; resolutely European approach to development; creation of a training, technological expertise and engineering centre; increasing number of PPP-NGO ventures; support policy for marine protected areas in the EEZ.

Priority

This ambitious vision requires French then European resources for the development of knowledge of deposits and their environment to be concentrated within a visible centre, before putting forward sustainable exploitation methods.

Legal Aspects

Marine mineral resources come under a legal regime that is dependent on their location, either within the legally defined continental shelf or in the deep sea beyond the limits of State jurisdiction, known as the Area. Here it is worth explaining why the continental shelf is referred to as "legally defined" and what is meant by the Area.

The 1982 United Nations Convention on the Law of the Sea (UNCLOS) provides a definition of the continental shelf which breaks away from that of the previous convention from 1958, quite close to geologists' conception of the continental shelf. UNCLOS aligned its definition of the continental shelf with that of the exclusive economic zone (EEZ), independently of all depth or exploitability criteria defined in1958. The new continental shelf is the area over which a coastal State exercises sovereign rights up to the 200 nautical mile limit, measured from its coasts.

The distance criterion was imposed by harmonisation with the EEZ. This tendency led to an innovative legal outcome: that of the possibility of extending the continental shelf beyond the 200 nautical mile limit. A State can apply for such an extension for up to 350 nautical miles, and even beyond, in certain conditions.

Institution of the Continental Shelf

The advantage of the institution of the continental shelf is to recognise the State's exclusive exercise of sovereign rights for the exploration and exploitation of its natural resources. Article 77 of UNCLOS outlines the extent and nature of these rights. Two points are worth mentioning: firstly, the exclusive nature of these rights means that if the coastal State does not explore the continental shelf or exploit its natural resources, no-one may undertake these activities without the express consent of the coastal State. This demonstrates the strategic importance underlying the sovereign rights expected of the extension of the continental shelf. The second point confirms and supports the previous point in that the sovereign rights do not depend on effective occupation or on any express proclamation.

It is within this context that the Continental Shelf Act of 31st December 1968 (and its implementing decrees) introduced the national legal system serving as a basis for access to marine mineral resources. Considerable developments have come about in the case of French overseas territories with a specific status, for instance New Caledonia or French Polynesia. These territories have the power to regulate access to natural resources (exploration of the continental shelf, exploitation). This trend, which is confirmed by recent transfers of State competence, is set to become more marked based on the control, by these territories, of their development. This movement could, in the long run, also be implemented for overseas territories which are thought to still be placed under State competence for the definition of rules relating to exploration of the continental shelf and exploitation of natural resources.

The Area is legally defined in the first lines of the UNCLOS Convention as the seabed and ocean floor and subsoil thereof, beyond the limits of national jurisdiction. Activities in the Area means all activities of exploration for, and exploitation of, the resources of the Area. The Area and its activities are placed under the responsibility of an organisation specially established by UNCLOS, the International Seabed Authority (ISA), of which France is a member following its ratification of UNCLOS in 1996.

The legal framework for activities relating to mineral resources in the Area is provided by Part XI of UNCLOS, and by Annex III on "Basic conditions of prospecting, exploration and exploitation". Part XI is institutional in that it outlines the ISA's decision-making mechanisms and details its composition with three principal organs, the Council, the Legal and Technical Commission (LTC) and the Secretariat. It is through the interaction of these organs that the texts that will make up the Mining Code are elaborated and adopted.

Regulations

The first regulations adopted were the Regulations on Prospecting and Exploration for Polymetallic Nodules in the Area in July 2000. In May 2010, the Regulations for Prospecting and Exploration of Polymetallic Sulphides were adopted. The regulations have points in common which draw upon the main elements of the international regime and which are based on the principle of the common heritage of mankind laid down in article 136 of UNCLOS.

These common elements are as follows:

- the division of the area to be explored into two parts of equal estimated value, enabling the designation of a reserved area for the ISA's commercial entity, the Enterprise. The ISA is thus able to develop its reserves without having to conduct any exploration or prospecting.
- the choice, in theory, is not made by the applicant but by the ISA.
- the contract is valid for a fifteen-year period and may be extended.
- fees must be paid at the time of submitting an application. This is only the case for sulphide contracts, the case of nodules is managed differently for historical reasons. The applicant can choose between payment of a fixed fee of US $ 500,000, or payment of a fixed fee of US $ 50,000 dollars and, when the time comes, an annual fee calculated based on a revenue-sharing provision for the Enterprise as a joint-venture partner.
- the contractor's rights are guaranteed, as is exclusivity for exploration.

The 2010 sulphides regulations and contracts granted within this framework constitute common international mining law. Those directly concerned are States Parties to UNCLOS which, excluding the case of an application for themselves, must grant sponsorship to all entities, whether public or private, that apply for their sponsorship. This State sponsorship calls for careful examination as the ISA has submitted a request for an advisory opinion to the International Tribunal for the Law of the Sea in Hamburg on the question of the responsibility of such a State in the case of default of the sponsored entity. Dispute over the contractor's obligations and dispute over environmental damages are liable to be the focus of the analysis by ITLOS.

The role of the LTC is to provide an opinion on the application. It must, in particular, ensure that the application is respectful of the marine environment and does not hinder navigation or fishing. The role of the Council is well defined as the decision-making body that grants approval. Application rejection is an exceptional case, because it requires a qualified vote, the conditions of which are difficult to meet. China, in May 2010, and Russia, in January 2011, submitted exploration applications and there is little chance of these applications being rejected, as they are not in competition; the first is located in the Indian Ocean and the second in the Atlantic Ocean.

Future Prospects

By acting in this way, with a rapid procedure that overcomes obstacles which could be raised by conflicts due to overlapping sectors, the ISA intends to give an image of efficiency and sound governance, in concordance with the renewed legitimacy perceived in international bodies as soon as resources of areas beyond national jurisdiction are addressed. This reveals an avenue that a certain number of States Parties to UNCLOS fully intend to explore for deep-sea genetic resources when the time comes.

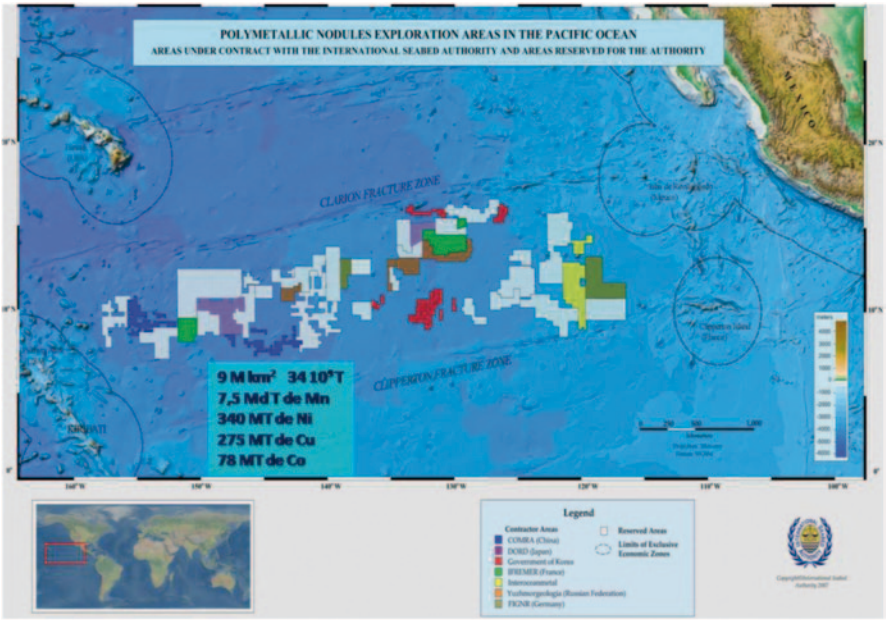


Fig. 1.10 Position of "nodule" contracts in the Clarion-Clipperton Zone

Similarly, the ISA's development prospects will take advantage of the authorisation it is granted, by articles 143 and 145 of UNCLOS, to promote marine scientific research in the Area and to ensure protection of the marine environment. The growing number of applications is likely to help to justify the role of the ISA (cf. Fig. 1.10). The links that exist between the elements of the ISA's mandate and activities in the Area will greatly boost the authority's legitimacy. We can fairly safely predict a consolidation phase of the ISA, which is set to receive increasing support, both from developing or emerging countries and developed countries (France, United Kingdom), to win over environmental NGOs and to become a centre of international deep-sea scientific expertise.

In an analysis of legal aspects, the question of natural resource exploration contracts and that of the technological evolution of access to these resources cannot be dissociated. The major constraint which faces this field is demonstrating the management of the risks these activities impose on the marine environment. The ISA is responsible for risk management for the Area, just as the State is responsible for risk management for the continental shelf, placed under its sovereign rights.

Thus, based on the strict right of access to marine natural resources, legal practices are likely to shift towards a form of law based on the precautionary principle, while gradually incorporating sustainability into all exploitation of the concerned ecosystems. We can therefore reasonably expect the authority of the ISA to grow over the years, due to the utility of an uncontested supranational structure in this field.

Technological Innovation Challenges

The potential exploitation of deep-sea mineral resources reveals major technological challenges. As this industry is new, the countries and industrial firms that manage to anticipate and master exploration and exploitation technologies will be able to draw the benefit of their know-how on a global scale.

Furthermore, the inevitable long term rise in raw material prices raises questions and concerns. The sector's economic stakeholders are aware of these weak points. They know there are no definitively acquired advantages and that they must continually improve their competitiveness, in particular through innovation.

For this new, and therefore immature, industrial sector, leadership positions have not yet been taken on a global scale. France can still take some of the top places, as long as it promotes its quest for excellence and encourages the emergence of industrial players.

Exploration and Observation Technologies

The technological development of exploration systems suitable for extreme, deep-sea environments and related geological objects is a must. Monitoring of the environmental impact of any resource exploitation will also involve the development of observation and measurement techniques. In addition to vessels, existing or new technologies to locate and study these potential resources can be considered on three levels.

Regional Exploration Technologies

This is an essential stage before assessing resources and before studying the biodiversity related to fluid release. One of the aims is to detect physical or chemical anomalies in the water column in order to locate areas of fluid emissions. The tools deployed are designed for mapping (multi-beam echo sounder), bottom acoustic imagery (sonar), water sampling to detect chemical tracers and physical measurements in the water column. In current conditions, these techniques are effective in locating active fluid release, but developments are necessary to locate the most promising fossil systems for mineral resources.

In order to ensure France maintains a global leading position in this field, it is essential to develop new tools to implement more efficient exploration and identification strategies. Several avenues are emerging: development of acoustic detection of fluid plumes in the water column using bathymetric sonar and ADCP techniques; "marinisation" of chemical in situ analysis techniques close to the seabed (mass spectrometers GC-MS, in order to detect organic tracers emitted by the fluids, Raman techniques for analysis of solids…). Some of this equipment will need to be adapted to vectors such as Autonomous Underwater Vehicles (AUV) and Remotely Operated Vehicles (ROV).

Site Study Technologies and Resource and Biodiversity Evaluation

When sites are identified, scientific understanding of geological, geochemical and biological processes implies work requiring submersibles (manned, remotely operated or autonomous vehicles) to be deployed. These vehicles can be used for more precise exploration on a local scale and for specific sampling.

Like in the exploration phase, many development are necessary to retain a global leading position and implement more efficient strategies. One of the essential steps concerns bathymetry and ultra-high resolution imagery (tens of centimetres) near the ocean floor. Continued development efforts are required to determine the dimensions of all vectors and sensors for 6,000 m depths. Specialised tools should also be developed to more accurately quantify hydrogen flows and progress is required to quantify the presence of hydrates in sediments from seismic data. The evaluation of mineral deposits requires knowledge of their volume and composition. To locate fossil sites and assess their dimensions, geophysical techniques (gravimetry, magnetics, electric methods) need to be “marinised”. Finally, the evaluation of the wealth and value of deep-sea mineral deposits requires sampling using core drilling tools operating directly on the seabed.

Environmental Monitoring and Preservation Technologies

In order to minimise the impact of deep-sea mining, specialised tools are required to establish biological reference conditions. These tools should also be able to identify disturbances related to natural geological activity (volcanic activity, plate tectonics, chemical and particle emissions by fluids) and anthropogenic disturbances related to mining. These approaches require the development of tools able to monitor temporal variability. An important point concerns the observation of temporal evolution of biological populations (observatories) and the development of autonomous systems (entrainment separator, current meter) to determine particle emissions related to human activities.

Mining Technologies

The development of deep-sea exploration and exploitation technologies is one of the major scientific and technological undertakings of the past 50 years. This dual goal was brought by industrialised societies to design the best means to explore and exploit the sea. Since the mid-20th century, we have discovered that the sea is teeming with minerals sought by industry. Submarine explorers began to gather data on this wealth in terms of energy and mineral reserves. Yet, in many respects, this wealth could just as well have been on the Moon, given how difficult it appeared to discover and extract them.

Offshore oil drilling equipment is now able to control drill bits 6 km from the seabed. Vessels can control mobile vehicles attached to them positioned thousands of metres below the surface, and sometimes in difficult sea conditions. To visually explore the deep-sea environment, humans are now capable of operating in a completely obscure environment in which every square centimetre is crushed under half a tonne of water.

Whether on land or at sea, only four methods are available for collecting minerals: surface scraping, excavation, digging tunnels to access subsurface deposits and drilling into and fluidising the deposit. The difference with deep-sea mining is that operations must be carried out underwater, and are controlled remotely from a floating surface platform. At each stage in the process, according to the nature of the deposit, the mass handled diminishes and waste is discharged.

To date, no long-lasting commercial operations to collect solid minerals have been carried out at depths of over 200 m; however the first trials conducted in 2010 by Nautilus Minerals with polymetallic sulphide collection systems at depths of 1,700 m, where the sulphides were easily detached from the seabed, showed that, from a technical point of view, nothing is currently preventing the exploitation of this type of deposit.

The progress made in terms of deep-sea drilling, trench digging and oil production capacities have considerably extended the range of technical resources available, however these resources must undergo major modifications to be suitable for the more selective extraction procedures required for harder mineral deposits.

With the notable exception of those applied to diamond mining, most deep-sea exploration and exploitation techniques were originally designed for shallow waters and their use was gradually extended to respond to needs. It is therefore necessary, in order to fill the gaps, for techniques applicable to deep waters to be developed by perfecting traditional systems, many of which are borrowed from other industrial sectors.

Results and Recommendations

Results

The conclusions are distinguished by mineral type and by related site.

Hydrothermal Sulphides

The exploration and potential exploitation of hydrothermal sulphides will be the focus of all challenges: geopolitical (for international waters), within the framework of the introduction of ISA permits; environmental, with probable conflicts over site protection and exploitation conditions; scientific (volcanic and tectonic processes, rock and fluid geochemistry, specific metallogeny, biological resources…) and economic.

Crusts

The exploitation of crusts will not come to fruition before 2030 (uncertain exploitability, technological availabilities…) despite their high potential. However, the richest areas are in the EEZ of Polynesia. Work on the seabed is required to determine areas of interest, with continuity favourable to exploitation.

Polymetallic Nodules

The exploitation of polymetallic nodules appears possible in technical terms, hypothetical in economic terms and of little relevance in national terms given the existing land-based resources. Nevertheless, there is now renewed interest in nodules and crusts due to the presence of rare metals (rare earths, molybdenum, tellurium, vanadium, zirconium, thallium…) which were not taken into account in the past. Several countries have conducted systematic analyses of their collections in order to determine the samples and areas with the highest rare metal contents.

Natural Hydrogen

In the current state of knowledge, exploitation of natural hydrogen cannot be considered until the very long term. This is a recent discovery made by Ifremer on hydrothermal systems associated with mantle rock. Scientific knowledge of processes needs to be improved and flows quantified.

This prospective analysis conducted in collaboration with all the public and private partners involved, as well as the proposals of the French Blue Book "A National Strategy for the Sea and Oceans", supported by those of the European Commission, clearly show the changes in global raw materials markets. Over and above the price surge of many metals over the past years (zinc, copper…), European States must take into consideration their growing dependence on imports of metal minerals and so-called "high-tech" (also known as rare or strategic) metals such as cobalt, platinum, rare earth metals, gallium, germanium, indium and titanium.

However, at the current growth rate, global demand for these types of materials is set to double over the coming 5 years. Consequently, demand for certain rare or strategic metals will rise sharply, notably in connection with the evolution of environmental technologies, telecommunications and defence markets, with probable bottlenecks in supply, related to the strategies of the countries where these resources are found (China, South Africa, Brazil, Russia…).

Furthermore, in addition to exploration to locate new land-based deposits, we will need to look increasingly to the sea to meet global demand for raw materials. New perspectives are opened up by potential subsea mineral resources: hydrothermal sulphides, nodules and cobalt- and manganese-rich crusts. These perspectives lead the way to new scope for exploration and exploitation, which in some cases has already begun, of deep-sea mineral resources.

Access to these strategic metals requires, firstly, scientific knowledge of the geological and geochemical processes leading to the formation of these potential resources, without neglecting knowledge of biodiversity and ecosystems, and, secondly, the development of new exploration, extraction and processing tools.

For a few years now, the mining industry has been taking an interest in submarine hydrothermal mineral deposits. Exploration applications have been submitted for several offshore hydrothermal fields in the Western Pacific by companies preparing to exploit hydrothermal deposits in Papua New Guinea and north of New Zealand (Nautilus). The issue of access to mineral raw materials gives rise to increasingly visible international competition. Faced with this rapid evolution, the ISA adopted Regulations on Prospecting and Exploration for Polymetallic Sulphides in the Area at its 16th session on 7th May 2010, authorising applications for exclusive exploration rights in international waters. As soon as this text came into force, the China Ocean Mineral Resources R & D Association (COMRA) submitted an application in December 2010. In January 2011, it was Russia's turn to make its application.

Stakeholders are therefore setting the wheels in motion around the globe. On a world scale, around 60 licenses would be enough to cover all the ridges concerned. The countries having submitted applications will also have an obvious advantage: these licenses provide exclusive exploration rights, preventing *ipso jure* all other operations in that area.

France's Position

Within this backdrop, France's industrial, technological and scientific interests must be supported and united, as a pioneering country for deep-sea technology and knowledge since the 1970s.

France has a coherent set of scientific expertise and technological skills in the fields of the deep sea and mining: Ifremer, BRGM, CNRS and universities among public establishments, Technip, Areva, and Eramet within the private sector. It thus has the potential to conduct scientific research and develop innovative technologies for future access to mineral resources. It also possesses the world's second largest EEZ, currently being extended through the Extraplac programme. Given this context, France is duty-bound to define a strategy and identify priorities.

It is with this objective in mind that the Wallis and Futuna programme was run in 2010. This first campaign, Futuna 2010, which ran from 3rd August to 23rd September 2010, was an outcome of the agreement on the first exploration of the French EEZ around the islands of Wallis and Futuna in order to identify active and inactive hydrothermal sites and to study the associated biodiversity. This campaign was made possible thanks to a public-private partnership involving the French Ministry of Ecology, Sustainable Development, Transport and Housing, the French Marine Protected Areas Agency, Ifremer and BRGM among public organisations and Technip, Eramet and Areva for the private sector. Other academic organisations, CNRS-INSU, Institute of Earth Physics of Paris (IPGP), French Atomic Energy

Commission (CEA), University of Western Brittany (UBO), were also involved. This campaign resulted in the discovery of a recent, vast volcanic area (new ridge, new volcanoes) and the identification of several hydrothermal deposits.

Recommendations

The priority actions proposed for France can be divided into eight avenues.

Scientific Knowledge and Development of Potential

This action implies joint, multidisciplinary research geared towards knowledge of the seabed and protection of biodiversity, involving public and private players (notably in the fields of marine technologies, metallogeny…) as well as NGOs competent in the field, in particular in terms of biodiversity, site resilience… This work should be conducted in synergy with national and European research on mineral resources (French research alliances, reflection on French overseas territories, National Research Agency, European Union Research and Development Framework Programme).

This approach should lead to the establishment of a national geological and biological seabed research programme, including targeted exploration of the French EEZ and the international seabed, over a ten-year period; this programme should include new exploration technologies (high resolution, three dimensions, modelling…), a programme of marine campaigns using flow monitoring tools, evaluation of biodiversity and management of the information produced (geographic information systems (GIS), sensitive information banks…).

In 2011, a second exploration campaign was run in the Wallis and Futuna area. Given international pressure on applications, this type of approach should be extended to other areas, by seeking optimal use of the means available at sea and of the available national scientific forces. This action should be designed and run by a French or, from the outset, a European consortium.

Public-Private Partnership

The goal is to develop a French deep-sea mining centre. Based on an approach inspired by the French Grenelle Environment Round Table, this involves supporting a mining project public-private partnership, by drawing upon the development of French technologies and industry, both for exploration techniques and for the technological research required to build an extraction pilot. This would result in an industrial pilot for metal extraction (in the EEZ of Wallis and Futuna and/or other international zones).

Search for Strategic Metals in Existing Collections

Rare metals have not always been detected in samples collected over the past decades. A major analysis effort will need to be made on existing collections, in order to determine fluctuations in concentrations of rare elements and to understand concentration processes in the richest samples. However, the knowledge gained shows that several rare metals are concentrated in oceanic mineral deposits. In the case of hydrothermal sulphides for instance, minor elements are found alongside the main metals. These sites, whose locations are known, could be considered to be strategic reserves for base elements and certain rare metals, if significant enrichment is confirmed by such studies.

Reinforced French Presence at the ISA

The aim is to boost French research in international waters with associated measures encompassing the maintenance of nodule licenses and, moreover, an active presence within the ISA. To do so, greater participation, at a high level of expertise, is required in the Legal and Technical Commission which will address questions of governance, especially in terms of environmental governance, marine areas to be protected and contract monitoring.

Submission of an Exclusive Exploration Application for Sulphide Deposits

An exclusive exploration application needs to be made to the ISA as soon as possible. This application may be based on a public/private partnership with the possibility of sponsorship by a single State (France) or several States, whether European or not. In this regard, specialists must therefore discuss the selection of areas with the highest potential relatively soon.

Contributing to a European Strategy

(intergovernmental organisation on strategic metals)

Given its strong position in terms of scientific expertise and technological skills, France should play a major, if not leading, role in the development of a European strategy, by proposing for instance an intergovernmental organisation on strategic metals, by drawing upon initiatives in progress, whether bilateral (German-French Association for Science and Technology, notably with BGR in Hanover) or within the framework of the G3: IFM-Geomar in Kiel, the National Oceanography Centre (NOC) in Southampton, and Ifremer. Training aspects on a European scale should also be taken into consideration in order to maintain research and development and technological implementation capacities in this field.

Development of Exploration and Exploitation Technologies and French Industry

The public/private partnership should address both exploration and exploitation technologies in order to promote synergies and prevent a delay in exploitation. One of the barriers is the development of extraction pilots to validate the integration of known, yet complex, technological solutions. Financial arrangements and business models remain to be defined. In terms of mineral processing and metallurgy, the processing of ocean minerals will need to be adapted, requiring technological research capacities for certain crucial aspects: corrosion (SH), reliability, impacts, vent exploitation (natural H_2) and exploration technologies.

EEZ Heritage Management

The need for a general inventory of potential resources and their locations constitutes a prerequisite for planning access priorities and possible development. This initiative requires the conditions governing the exploration and exploitation of deep-sea mineral resources in EEZs to be clarified (national mining law to be completed, extralateral right, financial transparency, definition of exploitation protocols…). In terms of living organisms, a certain number of marine protected areas should be established in the EEZ at quite an early stage.

Within this promising context of deep-sea mineral resources, although lacking important knowledge in several fields and on various scales, skills and means must be gathered together to save time, improve efficiency and provide consistency. The priority is therefore to support and unite France's industrial, technological and scientific interests in order that it may continue to be one of the pioneering countries in deep-sea exploration and promotion.

Part II
Thematic Contributions

Chapter 2
Deep-sea Environment

Joëlle Galéron

The Deep Sea, the Planet's Largest Biome

The deep sea, defined as the part of the ocean over 1,000 m deep, covers 60 % of the Earth's surface, making it the planet's largest biome (homogeneous ecological formation). The geological, geochemical and physical conditions of the seabed and water column define varied habitats, sheltering specific biological communities. The ocean floor is composed of various distinct environments, including continental margins, abyssal plains, oceanic trenches, mid-ocean ridges and seamounts. Over 90 % of the deep seabed is covered with fine sediments composed of particles of biogenic (i.e. produced by living organisms), terrigenous, volcanic and authigenic (i.e. originating from the rock where it is found) origin: they are found on abyssal plains, but also on continental slopes. The seabed is however rockier on mid-ocean ridges and seamounts, as well as in some isolated areas of continental slopes, into which submarine canyons with abrupt cliffs may be cut. The marine environment is globally characterised by an absence of sunlight, high pressure, low and relatively constant temperatures, low currents and an oxygen content generally sufficient for animal life to develop. In the case of the total absence of dissolved oxygen, in specific situations and in small areas, only anaerobic bacteria can develop.

Energy Sources for Deep-sea Life

Despite the lack of light, the life found in the deep-sea environment relies almost exclusively on organic matter produced by photosynthesis. This occurs mainly in surface waters that light can reach; it enables the development of plankton and pelagic ecosystems in the water column. The residues of these networks settle on the ocean floor mainly in the form of a shower of small particles, supplying animal

---

J. Galéron (✉)
Centre Bretagne, Environnement profond, Ifremer, BP 70, 29280 Plouzané, France
e-mail: joelle.galeron@ifremer.fr

Y. Fouquet, D. Lacroix (eds.), *Deep Marine Mineral Resources*,
DOI 10.1007/978-94-017-8563-1_2, © Éditions Quæ 2014

communities in the deep-sea water column and on the ocean floor. This organic matter decreases as depth increases and also varies according to the level and rate of primary production in the surface waters. It can be supplemented by lateral supplies from continents, in particular near to submarine canyons cut into ocean margins, and can drain large quantities of matter from land.

In general terms, the deep sea is characterised by very low nutrient availability (1–10 g of organic carbon per square metre per year), which may vary on a seasonal basis, in particular in temperate regions but also on a multiannual or erratic basis according to the specific climate conditions. These abyssal environments are known as oligotrophic. There are however exceptions to this rule: hot fluid release areas on mid-ocean ridges, back-arc basins, volcanic arcs, active intraplate volcanoes and cold fluid emission areas on ocean margins. In these specific cases, the energy source is not solar light, but chemical compounds discharged by the fluids, used by micro-organisms to synthesise organic matter to feed exuberant animal communities, often known as an "oasis of life" in what appears to be an abyssal "desert".

Life in the Abyssal 'Desert'

The abyssal "desert" is mainly composed of plains covered in fine sediment that stretch across the majority of the ocean floor. The low nutrient flow to the seabed only allows very moderate biological productivity; deep-sea biological communities are characterised by a low biomass, which decreases as the depth increases. Large organisms (megafauna), visible to the naked eye, are rarely found. These environments were therefore long believed to be barren until the 1960s, when sediment sampling tools were developed; this revealed the presence of a living world, invisible to the naked eye, still poorly known today, composed of micro-organisms and animals measuring a few dozen microns (meiofauna) to a few hundred microns (macrofauna).

Although rare in the deep-sea environment, larger animals are nevertheless present; a few dozen to a few hundred per hectare can be found on abyssal plains in the Atlantic or Pacific Ocean. This fauna is composed mainly of animals that crawl along the ocean floor and feed on detritus particles settled there; this is the case for echinoderms (holothuroids (Fig. 2.1), asteroids, ophiuroids and echinoids) which often form the majority of this fauna. We also find organisms fixed in the sediment or on small hard substrates (protozoa, sponges, cnidaria) which feed on particles in suspension in the overlying water, animals that live in the sediment—worms (Fig. 2.2), bivalve molluscs, certain crustaceans—as well as a few fish and crustaceans that swim next to the bottom (Figs. 2.3, 2.4 and 2.5).

The macrofauna is mainly composed of polychaete annelid worms (Fig. 2.2), small peracarid crustaceans (Fig. 2.6) and gastropod and bivalve molluscs; a few dozen to a few hundred individuals can typically be found per square metre. The meiofauna is generally dominated by nematode worms (>90 % metazoa) and by foraminifera; their abundance can reach up to a few dozen per square centimetre. These communities mainly live in the first 5–10 cm of sediment, with decreasing

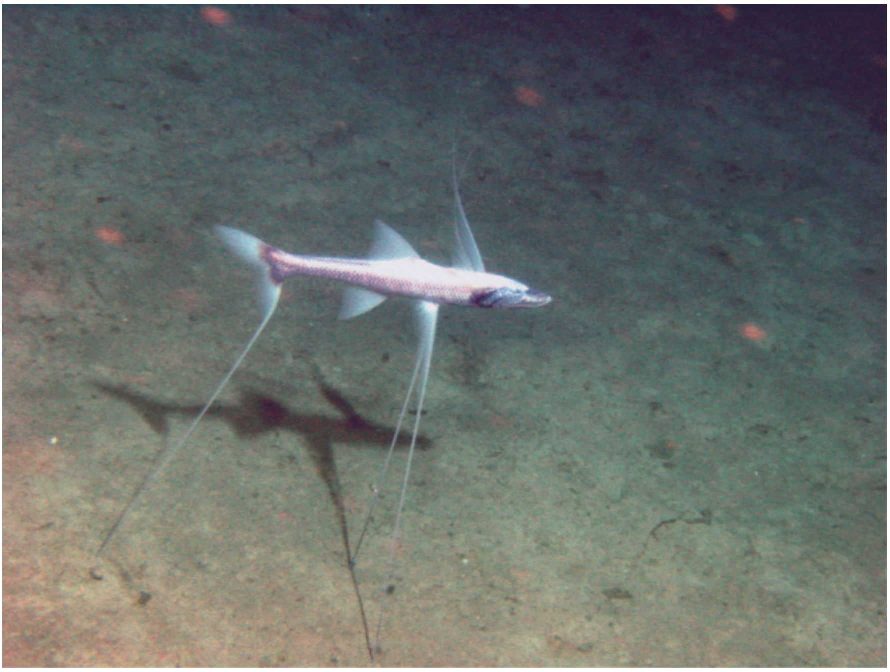


Fig. 2.1 Holothuroidea Psychropotes longicauda on nodule-covered floor of the Pacific

Fig. 2.2 Polychaete annelid worms, dominant group of sediment macrofauna

abundance in the deeper layers of the sediment column. Bacteria, omnipresent in all environments, form an essential component of deep-sea biological communities where they represent the largest share of the biomass, and play a vital role by recycling organic matter on the seabed. The structural traits of these sediment communities vary spatially with environmental parameters such as depth, latitude and all

Fig. 2.3 Tripod fish Bathypterois sp. on the seabed in the Gulf of Guinea

Fig. 2.4 Rattail fish Coryphaenoides sp. (grenadier) in the Atlantic

other related factors. However, it was not until recently that changes related to the seasons or other patterns were demonstrated, in particular in relation to variability in primary production at the surface in temperate areas, global climate change, or other erratic or recurrent climate phenomena.

Biological Diversity Similar to that of Rainforests in the Abyssal 'Desert'

The biological diversity of abyssal sediments remains poorly known. The main reasons for this are as follows: the considerable extent of this environment (around 300 million km^2), the difficulties in access resulting in clear undersampling (a few hundred square metres for macrofauna, a few square metres for meiofauna), the

Fig. 2.5 Decapod crustacean from the Polychelidae family on the abyssal ocean floor

Fig. 2.6 Small peracarid isopod crustacean living in deep-sea sediment

small size of organisms and the small (and constantly falling) number of taxonomists on a global scale.

Several recent studies have shown that over 90 % of animal species collected in the abyss are unknown; as for bacterial diversity, there is an even greater lack of knowledge.

Despite these difficulties, scientists have been able to show that the biological diversity of abyssal sediments on a local scale is very high. Several hundred species of protozoan and metazoan invertebrates can be found in an area measuring quarter of a square metre. These estimates are considered to be minimal, as recent progress in the field of molecular taxonomy appears to indicate that this local diversity is in fact higher. Furthermore, few data are available, and it is therefore very difficult to correctly assess species' geographic distribution and the global diversity of the abyssal sediment community. However, the living environment of these sediments is now considered to be an exceptional source of biodiversity, comparable to that of rainforests.

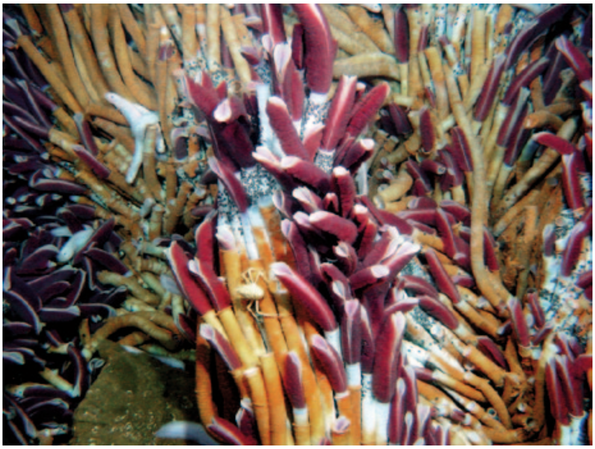


Fig. 2.7 Giant worms Riftia pachyptila on the East Pacific Rise

Hydrothermal Vent Ecosystems

The first hot vents were discovered in the Pacific towards the end of the 1970s, at a depth of around 2,500 m. Since then, many hydrothermal vents have been and continue to be discovered on mid-ocean ridges, but also in back-arc basins, volcanic arcs or on active intraplate volcanoes. The exceedingly hot fluid (up to 400 °C) that is expelled contains large quantities of reduced chemical elements, such as hydrogen sulphide or methane.These compounds act as a foundation for an original and highly productive food chain, based on bacterial chemosynthesis. Organic matter is synthesised by bacteria which use chemical energy, rather than light energy as is the case for green plants in photosynthesis. A wide range of microbes colonise these environments from the hottest areas to the periphery, where the temperature is low.

Alongside these microbes which use sulphides and inorganic carbon, animal communities develop, proliferating in the area where hot fluid mixes with cold seawater, despite the toxicity of this mixture. They are made up of dense colonies of "engineer" species which provide a habitat for several hundred related species. Each "unit" gathering hydrothermal vents shelters a few characteristic "engineer" species. For instance, on the East Pacific Rise, four species dominate the hydrothermal ecosystem: the giant worm *Riftiapachyptila* (Fig. 2.7), the giant clam *Calyptogenamagnifica*, the mytilid *Bathymodiolusthermophilus* (Fig. 2.8) and the Pompeii worm *Alvinellapompejana*. Microbial mats, limpets, polychaete and nemertean worms, amphipod crustaceans, crabs, fish… live in various combinations with these species to form exuberant oases of life, structured in concentric circles around vents according to each species' nutritional needs and resistance to aggression by the fluids.

In the immediate environment of these hydrothermal communities, filter-feeders can be found, as can giant sea anemones (Fig. 2.9) or sponges which enjoy the environment's biological wealth. On this ridge, over 200 species living in hydrothermal systems have been discovered, almost all of which are new and endemic. On the Mid-Atlantic Ridge, swarms of shrimp (Fig. 2.10) and mytilids dominate hydrother-

Fig. 2.8 Cluster of mytilids on an active hydrothermal chimney on the Mid-Atlantic Ridge

Fig. 2.9 Giant sea anemone on the periphery of an active hydrothermal site on the East Pacific Rise

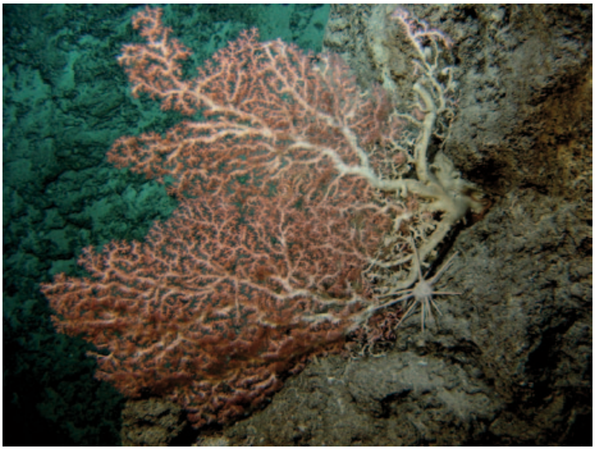


Fig. 2.10 Shrimps Rimicaris exoculata around a hydrothermal chimney on the Mid-Atlantic Ridge

Fig. 2.11 Coral and cidarid urchin on the periphery of active hydrothermal systems on the Mid-Atlantic Ridge

Fig. 2.12 Cirripedes on the periphery of an active hydrothermal site in Lau Basin, Pacific

mal fauna; filter-feeders proliferate in the surrounding area. In the back-arc basins of the Western Pacific, hydrothermal fields can be colonised by large gastropods, mytilids, Alvinellidae worms, coral (Fig. 2.11), with, on the periphery, cirripede crustaceans (Fig. 2.12), sponges or brisingida asteroids. Even if the fauna of each unit is unique, all these hydrothermal ecosystems function in the same way.

Other Chemosynthesis-based Ecosystems

In the 1980s, the presence of chemosynthesis-based ecosystems was highlighted in various contexts, on ocean margins in the presence of cold seeps and in other environments: oxygen minimum zones, bitumen outcrops, and on skeletons of decomposing cetaceans. While cold seep animal communities are nourished by chemosynthesis, they are also, due to their situation, nourished by organic matter of pelagic and terrigenous origin. The lower toxicity of the fluid allows bathyal species to enter the ecosystem, leading to far more diversified populations than in the case of deep-sea hydrothermal vents. The study of relationships between hydrothermal species and cold seep species shows that, during evolution, changes have taken place between these environments, and that cold seep areas have acted as relay areas for the dissemination of hydrothermal species. These chemosynthetic ecosystems also possess resources in the form of methane hydrates.

Specific Seamount Ecosystems

Seamounts are prominent structures of variable size and shape, widely distributed across the world's ocean floors, mainly in the Pacific, but also the Atlantic and Indian Oceans. They can reach up to 4,000 m above the ocean floor. They are most often formed by volcanic activity and the effects of plate tectonics; some are active volcanoes and therefore feature hydrothermal ecosystems. Generally speaking, seamounts have specific characteristics making them a special habitat for deep-sea fauna.

While abyssal plains generally have low slopes and are covered with fine sediment, seamounts can have steeper sides; their topography can be complex due to the presence of terraces, canyons, calderas or craters; hard and soft substrates coexist in different thicknesses and compositions. Furthermore, such relief alters the hydrodynamic conditions of surrounding water masses. It creates turbulence and sometimes major upwellings of cold water rich in minerals, promoting high biological productivity both in pelagic and benthic areas.

The complexity of the topography and the nature of the substrate, as well as strong hydrodynamics and a high bathymetric gradient, are influential factors in the structure of seamounts' faunal communities. Filter-feeding species dominate the community of organisms fixed to hard substrates, in particular sponges and cnidaria (including coral), which form the main part of the biomass. Fauna associated with various crustaceans, molluscs etc. is also found. Pelagic fauna is also abundant, with a high proportion of fish. This makes these structures a prime target for fishing, which is now known to have major destructive consequences on these ecosystems. The sediment accumulated in hollows and cracks or at the base of seamounts is populated, like the neighbouring abyssal sediments, by many species of polychaetes, molluscs, peracarid crustaceans and other invertebrates and foraminifera. Moreover, the composition of seamounts' benthic communities is, like continental margins, mainly affected by the bathymetric gradient, reflecting gradients that evolve with depth (temperature, oxygen concentration, energy resource availability, pressure…). Knowledge of the endemism rate of species and connectivity between populations remains poor. They are believed to be related to various biotic and abiotic factors, the most important being distance between seamounts, hydrodynamics and larval dispersal capacities.

Environmental Impact of Possible Exploitation of Deep-sea Mineral Resources

Polymetallic Nodules on Abyssal Plains

Nodules represent one of the few hard substrates on abyssal plains. They are home to a specific biological community, quite different to surrounding soft substrates, and provide a hard substrate for large filter-feeders to fix on to. The initial consequence of their exploitation would therefore be to destroy this specific habitat, resulting in the local extinction of related fauna. Nodules could not be extracted without also removing the upper sediment layer on which they lie. Yet, it is in the top few centimetres of sediment that almost all small animal communities develop, whose local species diversity is very high and yet remains almost unknown. Recent work conducted under French licenses in the Clarion–Clipperton Zone resulted in the identification of over 10,000 invertebrates, measuring a few dozen microns, in an area of around 0.07 m^2 of sediment, among which taxonomists have been able to identify over 1,000 species according to their morphological characteristics. For the first time, it was also shown that the presence of nodules on the seabed influenced the structure of sediment communities, and that a sediment community disturbed by a dredging operation had not recovered its original characteristics after a period of 26 years. The restoration of sediment communities destroyed by mining would appear to take several decades, or even several centuries. The redistribution of sediment in suspension in the water column would also significantly disturb the deep-sea pelagic community and the benthic community over far more extensive areas than those exploited.

Resources Related to Hydrothermal Systems

The first hydrothermal sulphide mineral deposits were discovered in 1978 on the East Pacific Rise. They are found on all submarine structures of volcanic origin, at depths between 800 and 4,100 m. Their inventory is still largely incomplete; several hundred are thought to exist in the world's oceans.

The specificity of environments in which sulphide deposits develop is the possibility of the presence of hydrothermal vents, with which specific communities are associated. These ecosystems are of considerable importance. They function in an original way; unlike in the surrounding abyssal environment, their productivity is very high (incomparable biomass) and their specific diversity (with the exclusion of microbes) is low (a few hundred species identified to date). However, their faunal communities are original; 99 % of species are endemic, and some of them are "living fossils" having survived major extinction events. The biotope, high in compounds reputed to be toxic, is extreme, compared to all environments known so far. Microorganisms which proliferate in these environments also show very specific characteristics, growth at very high temperatures and original and heat-stable compounds.

Sulphide extraction would have destructive effects on hydrothermal ecosystems on a local scale. However, this environment is naturally very unstable due to volcanic activity, and the restoration of a hydrothermal system destroyed by sulphide exploitation can be expected to be relatively fast, taking a few years. The direct effects of large-scale exploitation would of course be more damaging and the resilience or restoration of biological communities longer and more random.

Communities of species fixed to sulphide deposits are far less well known that those of hydrothermal vents, on which the majority of scientific investigation efforts are focused. These communities would of course be destroyed during extraction, and those fixed to surrounding volcanic rocks as well as those colonising the sediment accumulated in dips could suffer the secondary effects of the redistribution of particle plumes on the seabed.

It was recently shown that hydrogen could be naturally produced in hydrothermal systems through the reaction of water with ferromagnesian minerals in rocks. These phenomena occur either at low temperatures at "inactive" serpentinized seamounts or at high temperatures at "active" hydrothermal chimneys. The inventory of sites producing large quantities of natural hydrogen is far from complete, however many of them have already been identified at depths of over 4,000 m.

The extraction of natural hydrogen could be expected to mainly have consequences on the hydrothermal ecosystem, chemically altering the environment on a local scale. These processes could result in the local extinction of biological communities associated with these environments. Furthermore, disturbance by hydrothermal plumes could also affect the dispersal of the larvae of organisms living in these systems, restricting gene flows between sites on a regional scale.

Cobalt- and Platinum-rich Crusts

The first systematic investigations of these resources began in 1981 in the Central Pacific Ocean. These crusts develop on indurated substrates, in conditions of strong currents and low sedimentation rates. They are often found on structures situated above the ocean floor, seamounts, at depths ranging from 400 to 4,000 m.

Recent efforts to study these environments have shown that these are "islets" rich in biomass and in biological diversity, for animal communities living both on the seabed and in the water column. However, these environments are still difficult for the scientific community to access and the inventory of their biodiversity remains quite incomplete, especially for small organisms. Benthic fauna is believed to be of the same type as that of hard bottoms featuring sulphide deposits, with many large organisms, such as corals and sponges, fixed to rocks. The consequences of the exploitation of these resources on benthic communities would be comparable to that of sulphide deposits, with the exception of damage caused to hydrothermal ecosystems, absent from these environments.

Environmentally-friendly Exploitation of Deep-sea Mineral Resources

Deep-sea mineral resources may be located in international waters, in areas governed by the rights of States (EEZ), or in the area inside the limits of national jurisdiction. Deep-sea mineral exploration and exploitation activities are conducted under the responsibility of sovereign States or the International Seabed Authority (ISA).

In the so-called Area (international waters in the high sea), the ISA introduced the Regulations on Prospecting and Exploration for Polymetallic Nodules in the Area in 2000 and the Regulations for Prospecting and Exploration of Polymetallic Sulphides in 2010; the regulations for cobalt-rich crusts are still under discussion. The general aim of these regulations is to identify the possible impacts of activities on the environment in order to take the necessary measures to preserve the environment and its biological wealth. These regulations were defined taking into consideration scientific knowledge and understanding of the technology to be implemented to carry out these activities. They may be periodically revised to take account of progress in knowledge and technological developments.

Seven exploration licenses have currently been granted for polymetallic nodules in the Eastern Pacific, one of which was awarded to France in 2001. The first two licenses relating to sulphides were granted in 2011, one to China and the other to Russia.

In 2004, Ifremer conducted a multidisciplinary campaign in the Clarion–Clipperton Zone, focusing on the geological and biological environment of the two main sectors covered by France's nodule license. The acquired knowledge together with that of the other license holders and many scientists specialised in abyssal biodiversity contributed to the proposal of a project to develop an environmental management plan for the Clarion–Clipperton Zone, currently under discussion at the ISA.

As for sulphides, protection measures have been implemented by national jurisdictions for four areas with hydrothermal systems. These four areas are the Endeavour Hydrothermal Vents Marine Protected Area in the North-East Pacific (Canada), the Guaymas Basin and Eastern Pacific Rise Hydrothermal Vents Sanctuary (Mexico), the Marianas Trench Marine National Monument in the US waters of the Pacific and the Azores Marine Protected Area on the Mid-Atlantic Ridge (Portugal).

Scientists are striving to provide decision-making bodies with their knowledge of deep-sea biodiversity and ecosystems, based on which recommendations are made for environmentally-friendly exploitation of resources. However, understanding of these environments remains patchy, and the recommendations are necessarily governed by the precautionary principle. Research programmes should be pursued and new methods and technologies developed to improve our perception of these "unknown abyssal treasures" (Figs. 2.13, 2.14, and 2.15).

Fig. 2.13 Cross-section of a nodule showing concentric growth rings

Fig. 2.14 Marine geology training

Fig. 2.15 Terrestrial geology training

Chapter 3
Rare and Strategic Metals

Yves Fouquet and Bruno Martel-Jantin

Context

In western countries, an increasing share of metals is imported. While the supply of metals used in everyday products requires to be reduced, many economic sectors could be considerably affected. A distinction should be made between base metals (iron, copper, zinc, lead…) and rare metals, little known to the general public, and yet at the heart of high technology industries.

Over the past few years, the rare metals market has been driven by China's and India's second industrialisation phase, and the development of their high technology industry. The information and new energies era creates demand for an increasingly wide range of metals, in particular: tantalum in mobile phones; indium in liquid crystal displays; gallium, cadmium, indium and selenium in new generation, high yield photovoltaic cells. These metals, of which the volumes traded are very low, are highly sensitive to temporary imbalances between supply and demand. The uses of rare metals evolve rapidly according to technological innovations and these metals can become strategic. They cannot be considered independently of the base metals with which they are generally associated in deposits (Fig. 3.1).

Y. Fouquet (✉)
Géosciences marines, Centre Bretagne, Ifremer,
BP 70, 29280 Plouzané, France
e-mail: yves.fouquet@ifremer.fr

B. Martel-Jantin
Bureau de recherches géologiques et minières (BRGM),
39–43, quai André Citroën, 75015, Paris, France
e-mail: bruno.martel.jantin@brgm.fr

Y. Fouquet, D. Lacroix (eds.), *Deep Marine Mineral Resources*,
DOI 10.1007/978-94-017-8563-1_3, © Éditions Quæ 2014

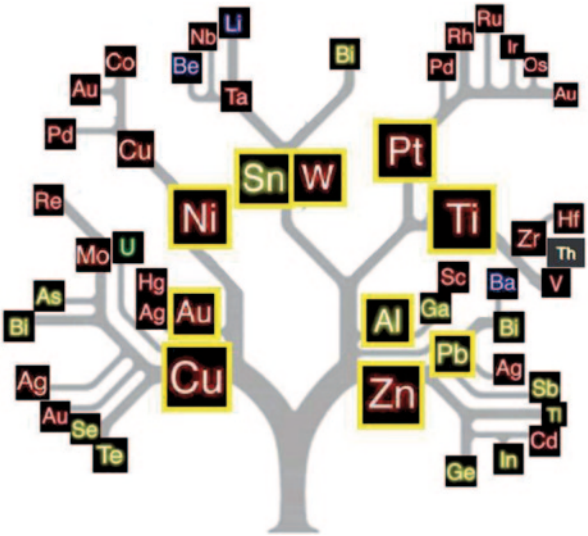


Fig. 3.1 Base metals and associated rare metals

Example of rare earth elements

Rare earth metals are a group of metals with similar properties and are comprised of scandium (Sc), yttrium (Y) and the 15 lanthanides. Despite their name, they are not rare: rare earth metals are found in the Earth's crust in larger quantities than copper or lead, at a concentration of around 0.08 %. The relative concentrations of the various lanthanides in these ores can vary from 50 % to a few percent. In terms of applications, the specificity of rare earth elements lies in their particular electronic structure which induces unique chemical, structural and physical properties, put to use in metallurgy, catalysis, glass-making, optics, ceramics, luminescence, magnetics, electronics and green technologies (wind turbines, photovoltaic cells, electric vehicles and energy-efficient lighting). One of the current major challenges concerns the manufacture of high strength magnets for electric motors. Their close chemical properties can sometimes make them difficult to distinguish.

China's monopoly in this field is very alarming. The United States, like other countries, including the European Union which published a report on this subject in June 2010, are concerned about the risk of China stopping exports, as the country possesses 97 % of world production of rare earth element ores and 37 % of known reserves. The United States and Australia have significant reserves (15 % and 5 % respectively), but have ceased to exploit them due to China's highly competitive prices and to environmental concerns. This preponderance alarms western countries which are seeking to diversify their supply, especially as China declared that it hopes to reduce its export quotas to 35,000 t per annum (out of a total production of 110,000 t) from

2010. The reasoning behind this decision is based on the desire to preserve rare resources and the environment. Chinese mineral ores contain a total of a few percent of rare earth oxides. This context further supports the need to diversify supply. Rare earth extraction and processing prove to be very costly and it may take two to ten years to open up new mines.

Several reasons point towards a restriction in the supply of rare metals: exhaustion of natural minerals; difficulty and/or cost of extraction and processing; dependence due to the limited number of mines and their location; increase in demand due to new technologies.

The pivotal question is whether the necessary mineral resources will be available in time and at an acceptable cost to meet the demand of both developed and emerging countries. With this as a backdrop, the notion of “critical metals” began to emerge a few years ago. A mineral is critical if it is both greatly used and subject to strong potential for supply restriction. Based on these criteria, the data, information and research required to attenuate potential restrictions in supplies of such a mineral can be determined. Criticality also depends on the degree of difficulty in rapidly finding substitutes.

For instance, platinum group metals and rare earths are fundamental for catalytic converters in the automotive industry. To date, no viable replacement product exists for these metals. Similarly, in response to an increase in demand for indium, used in the manufacture of flat screens, the price per kilo of indium rose from around US $ 100 in 2003 to US $ 980 in 2006.

Within this context, it is important to have good knowledge of data on the availability of these metals and to conduct research to fully understand natural concentration processes.

Factors Affecting Mineral Availability

In the medium and long term (over ten years), availability is related to five factors: geological (does the resource exist?), technical (can the ore be extracted and processed?), environmental and social (can metals be produced in an ecologically and socially acceptable manner?), political (how can governments influence availability through their actions?) and economic (can metals be produced at a cost that users are prepared to pay?).

Many existing and emerging technologies require minerals which are not available in western countries. Dependence on imports can expose a range of industries to political and economic risks. To maintain economic growth, it is important to be familiar with deposit types on a global scale, as well as the restriction potential and the solutions to remedy this situation. In the short and medium term, major restrictions in supply can occur, leading either to the unavailability of the mineral or a rise in prices.

The risks are as follows: major unexpected rise in demand for fully exploited minerals; small markets making it difficult to rapidly increase production to meet demand; production concentrated on a small number of mines, companies or producing countries; minerals extracted as by-products and whose availability is largely determined by the availability of the main product (e.g. gallium as a by-product of bauxite extraction); markets for which there is no significant recycling.

Critical Metals in the United States

The National Academies report on Minerals, Critical Minerals, and the U.S. Economy published in 2007 applies a criticality matrix to eleven metals: copper, gallium, indium, lithium, manganese, niobium, tantalum, titanium, vanadium, platinum group metals and rare earths. This list is of course liable to evolve over time. Of these eleven minerals, platinum group metals, rare earths, indium, manganese and niobium were considered to be the most critical due to their applications, the difficulty in finding substitutes and the risk for their supply. Although important applications exist for the other minerals (copper, gallium, lithium, tantalum, titanium and vanadium), they were identified as less critical, either because they had ready substitutes, or because the reserves were not potentially subject to restrictions at the time.

In order to identify and increase critical metal resources, the committee recommends improving information and analysis relating to minerals (in particular those that are or may become critical), collecting, disseminating and analysing data, funding activities, including basic sciences and research on essential minerals, in order to improve understanding of global availability and use of minerals.

More recently (December 2010), a specific criticality study on metals related to energy was conducted by the US Department of Energy (Fig. 3.2). It highlights the criticality of metals in the short term (0–5 years) and medium term (5–15 years) for energy needs and in particular renewable energies.

Critical Metals in Europe

The European Commission’s Raw Materials Initiative (COM 2008, p. 699) highlights the risks for Europe’s supply and competitiveness related to critical metals, while emphasising that these metals cannot be considered independently of the base metals with which they are generally associated in deposits. The EC document recommends an improvement in basic knowledge on geological potential, metal deposits and their exploration in Europe, as well as the development of more efficient extraction technologies, compatible with the maintenance of a sustainable environment and better use of mineral resources. A group is currently working to support the Commission on the possibility of a large-scale European exploration programme. In 2010, the Report of the Ad-Hoc Working Group on Defining Critical

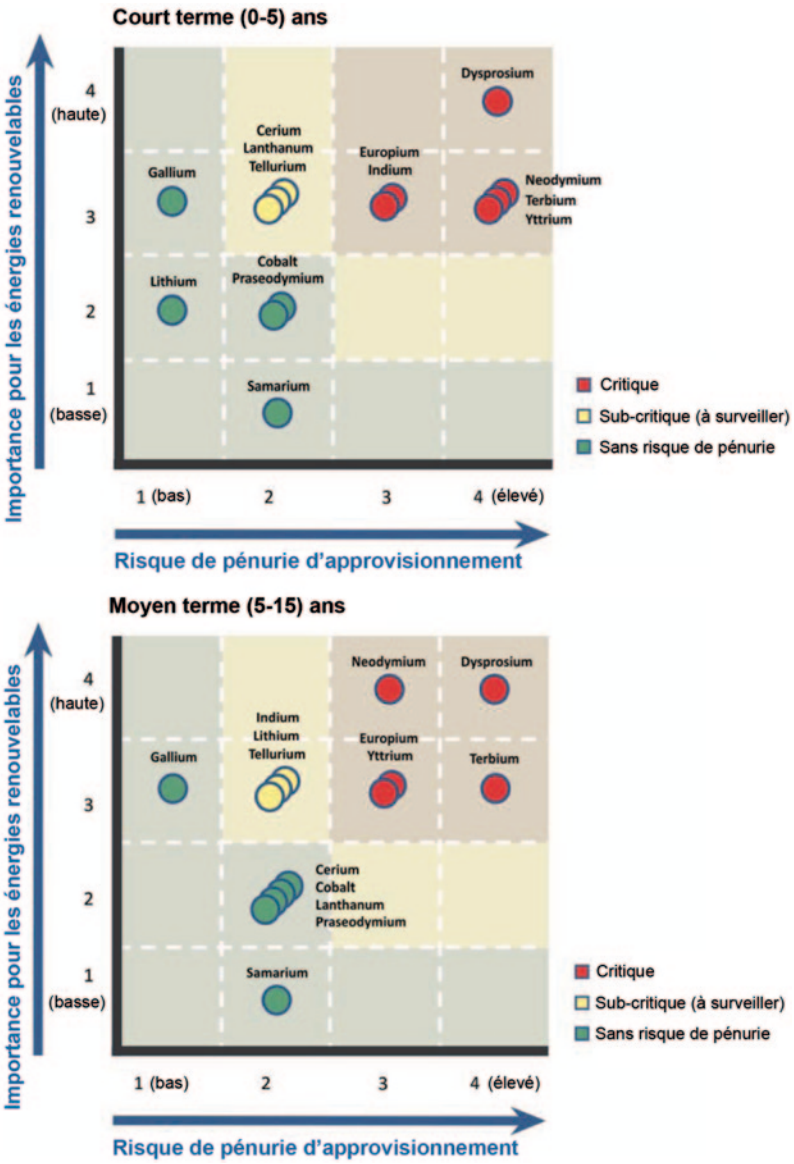


Fig. 3.2 Criticality matrix designed by the US Department of Energy for metals related to energy, with a short and medium term vision. (Source: US Department of Energy)

Raw Materials, entitled Critical Raw Materials for the EU, specified the degree of criticality of metals and certain materials, based on their economic importance and the risks of supply shortage. This resulted in a list of elements similar to the list established by the United States, in particular for elements such as platinum, rare earths, indium, tantalum and niobium.

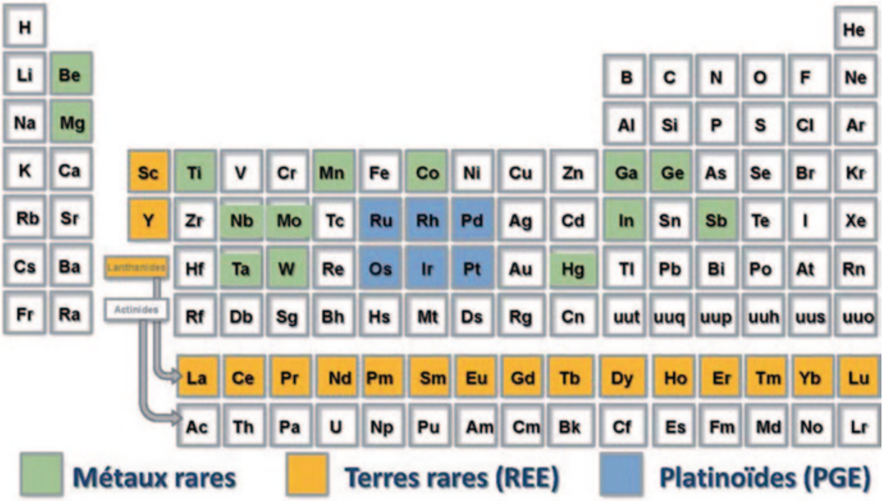


Fig. 3.3 Critical metals selected by the European Commission

In 2010, Europe drew up a list of critical metals (Fig. 3.3). The European report on critical metals considers that geological scarcity is not a criterion for determining criticality; in the same way, global reserves are not reliable indicators of long term availability. More relevant criteria concern the geopolitical and economic frameworks that affect supply and demand. Thus, growing demand for raw materials is driven by developing countries and new technologies.

Furthermore, several emerging economies, including China, tend to reserve their resources for their own exclusive use. This situation may be aggravated by a concentration of production in only a few countries. The European report considers that raw materials are "critical" when there are risks of supply shortage and when their impact on the economy is higher than that of other raw materials. Two types of risks are considered: firstly the supply risk, taking into account the political and economic stability of the producing countries, the level of concentration of production, the substitution potential and the recycling rate; secondly, the environmental risk, taking into account the impact that strict environmental measures taken by traditionally lax countries in this field would have on supply. On the basis of these criteria, fourteen elements are considered as critical, as they are of high economic importance coupled with a high availability risk.

Discussions are regularly held (Trans-Atlantic Workshop on Rare Earth Elements and Other Critical Materials for a Clean Energy Future, December 2010) between the European Union and the United State to increase collaboration in this crucially important field of mineral raw materials and in particular rare earths, vital for green technologies such as electric car batteries and wind turbines. Efforts are focused on ensuring better information sharing, improving mineral supply security and implementing a more unified approach to this challenge by the European Union and United States.

Critical Metals in France

In France, a list of strategic metals has been established by the relevant ministries (cf. Table 3.1). This list reveals France's heavy dependence for most rare metals. A list of land-based mines for rare metals should be drawn up, specifying the contents of these elements in order to determine the concentrations to be sought in other regions or other types of deposits and to improve supply security. There is currently no such list which can be used to rapidly assess the value of new indices on a given type of rare metal.

At the Ministry of Research and Higher Education, this question is mainly being addressed within the "Alliance" of institutes concerned by this field, known as ANCRE, which also deals with energy issues.

In the field of energy, the challenges are centered around rare and often critical metals. These metals are used in nuclear energy, batteries, renewable energies, as well as in energy saving processes, the development of new catalysts and chemical hydrogen storage. The challenges in the field of energy concern rhenium, selenium, tellurium, rare earths, uranium and vanadium. Seven major sectors of application have been identified, in which rare metals are or will be critical: nuclear with uranium; batteries with lithium, cobalt and rare earths; renewable energies and energy savings (in particular magnets for generators and electric motors) with rare earths, as well as photovoltaic with silver, cadmium, tellurium, indium, gallium and selenium; non-incandescent lighting with gallium; catalysts with platinum group metals and possibly chemical hydrogen storage with boron; high-temperature superconductivity with rare earths; fuel savings by improving engine performance and using lighter structures with nickel-rhenium for aeronautics and niobium for the automotive industry.

The ANCRE programme highlights the need for a full-fledged research programme to discover new mineral resources in continental masses and in the ocean, to exploit low concentrations or unconventional deposits, to determine their industrial value, to contribute to the evaluation or re-evaluation of land-based and sea-based mineral resources in French territories, their EEZ and partners' economic areas, and to develop efficient and sustainable exploration, exploitation and rehabilitation technologies.

The ANCRE programme proposes two fundamental avenues. The first consists in an inventory of critical metal resources through exploration and knowledge of the national territory, its EEZ and international partners' EEZs, in particular for lithium and rare earths. The second resides in the understanding of the concentration processes of so-called 'small metals'. The proposed research programme aims to develop knowledge of concentration processes for primary (lithium, rare earths) and secondary (by-products) elements in endogenous deposits of Zn, Ni, Cu and bauxites and argillites. Small metals are often by-products of base metals. They help to promote base metals considerably, in a context in which, as their concentration is gradually falling, their exploitation cost is on the rise.

Knowledge of small metal concentration processes is a considerable asset for the exploration, exploitation and strategic choice of base metal deposits, and is worth

Table 3.1 Concentrations of major and trace metals in the three main types of ocean deposits (Source: BRGM/Ifremer)

		Minimum and maximum concentrations			
		Nodules	Crusts		Sulphides
Major elements					
Zinc	ppm	512–1400	532–654	%	0.06–37
Copper	ppm	292–10200	729–11079	%	0–23
Iron	%	7–23	13–19	%	0.7–43
Sulphur	%	0.1–0.3	?	%	0–47
Manganese	%	7–26	13–23	%	0–3
Barium	ppm	1190–4185	1218–1257	%	0–34
Silicon	%	3–11	2–4	%	0.1–33
Titanium	%	0.5–1.3	0.8–1.3	%	?
Lead	ppm	450–1957	722–1721	ppm	30–142700
Phosphorus	%	0.1–1.8	0.4–2.4	%	?
Minor elements					
Nickel	ppm	2600–12800	2317–4389	ppm	1–915
Cerium	ppm	1–1684	547–752	ppm	?
Yttrium	ppm	131–267	193–218	ppm	?
Vanadium	ppm	470–865	495–682	ppm	?
Zirconium	ppm	70–802	397–630	ppm	?
Cadmium	ppm	3–12	<15	ppm	3–950
Germanium	ppm	?	?	ppm	1–226
Silver	ppm	0–1	<10	ppm	3–2100
Arsenic	ppm	158–1141	206–300	ppm	11–30000
Indium	ppm	<0.5	<7	ppm	1–204
Antimony	ppm	24–63	58–59	ppm	1–1005
Molybdenum	ppm	238–737	238–395	ppm	1–399
Cobalt	ppm	2400–8054	4326–11370	ppm	1–4931
Thallium	ppm	12–189	124–167	ppm	(2–43)?
Tellurium	ppm	3–216	?	ppm	(0–4)?
Selenium	ppm	0–52	<15	ppm	1–505
Tin	ppm	?	?	ppm	0–216
Mercury	ppm	0–360	?	ppm	2–274
Gold	ppm	?	?	ppm	0.05–20
Trace elements					
Chromium	ppm	9–180	12–26	ppm	?
Lithium	ppm	2–160	?	ppm	?
Beryllium	ppm	3–8	?	ppm	?
Boron	ppm	14–273	?	ppm	?
Scandium	ppm	5–19	7–14	ppm	?
Bismuth	ppm	6–53	12	ppm	0–63
Bromine	ppm	0–52	?	ppm	?
Hafnium	ppm	5–54	?	ppm	?
Tungsten	ppm	15–150	15–15	ppm	?
Uranium	ppm	7–16	9–12	ppm	0–8
Niobium	ppm	34–74	67–105	ppm	?
Fluorine	ppm	0–0	1–1	ppm	?
Caesium	ppm	2–157	?	ppm	?

Table 3.1 (continued)

		Minimum and maximum concentrations			
		Nodules	Crusts		Sulphides
Rare earths					
Lanthanum	ppm	36–343	155–224	ppm	?
Praseodymium	ppm	25–158	?	ppm	?
Neodymium	ppm	35–289	?	ppm	?
Samarium	ppm	9–53	?	ppm	?
Europium	ppm	6–72	8–8	ppm	?
Gadolinium	ppm	5–50	?	ppm	?
Terbium	ppm	4–31	?	ppm	?
Dysprosium	ppm	4–58	?	ppm	?
Holmium	ppm	5–18	?	ppm	?
Erbium	ppm	2–32	?	ppm	?
Thulium	ppm	2–20	?	ppm	?
Ytterbium	ppm	2–27	22–22	ppm	?
Lutetium	ppm	0.2–4	1–1	ppm	?
Platinum group metals					
Platinum	ppb	54–777	859–1304	ppb	(<100)?
Palladium	ppb	2–6	?	ppb	?
Rhodium	ppb	12–23	?	ppb	?
Ruthenium	ppb	14–21	?	ppb	?
Iridium	ppb	4–9	?	ppb	?
Rhenium	ppb	?	?	ppb	?

interpreting in two main areas: primary deposits for zinc (Ge, In, Cd), copper (Te, Se, Au, Ag) and nickel (Pd, Au, Co) and secondary deposits for aluminium (Ga, Se) in bauxites and laterites and heavy rare earths in clay and associated mineral ores.

Rare Metals and Marine Mineral Resources

Rare metal concentrations can be rather contrasting according to mineral deposits, but also according to the environments in which they are formed. Rare metals have not always been detected in samples collected over the past decades. A major analysis effort will need to be made on existing collections, in order to determine fluctuations in concentrations of rare elements and to understand concentration processes in the richest samples. However, the knowledge gained shows that several rare metals are concentrated in oceanic mineral deposits.

The base metals contained in nodules are iron (7–23 %), manganese (7–26 %), copper (292–10,200 ppm), nickel (2,600–12,800 ppm) and cobalt (2,400–8,054 ppm). These are the metals that have thus far been considered in economic estimations. Copper is found at concentrations on average twice as high as those of large copper mines operated in the Andes. Nevertheless, several studies show that nodules can be rich in light rare earths, in excess of several hundred grams per tonne (ppm). Other elements such as thallium can be present at concentrations of several hundred ppm. Nodules can also be considered as strategic reserves for base metals and certain rare metals. Several countries, including the United States and Germany, have undertaken to resume analyses of their collections of nodules using modern analytical methods in order to determine the variability in the composition of minor elements and in particular rare earths.

The chemical elements concentrated in crusts are rather similar to those of nodules. There are however variations for rare earths, platinum and cobalt which tend to be significantly more concentrated in crusts. Rare earth concentrations can reach a few thousand ppm in certain hydrogenated crusts, compared to a few hundred ppm in nodules.

Rare earths are extracted from seawater and the higher concentration in crusts is related to their lower growth rate.

Hydrothermal sulphides are characterised by very high base metal contents in relation to crusts and nodules. The sum total of copper and zinc frequently exceeds 15 %. As these are sulphide deposits, the sulphur content is very high and the iron content varies between 1 and 43 %.

Several minor elements are found alongside the main metals. Copper ore deposits, characterised by their formation at temperatures of over 300 °C, may also be rich in selenium, cobalt, nickel, molybdenum, tellurium, bismuth and gold. Zinc ore deposits, formed at between 100 and 250 °C, are often rich in cadmium, lead, arsenic, antimony, germanium, indium and barium.

Notes

1. The minimum and maximum values presented represent average values for the sites. Certain specific mineral associations can have far higher concentrations.
2. Data in brackets (2–43)? Only calculated for a few sites.
3. Many concentrations are calculated based on old analytical methods and would be worth reviewing using quicker, more sensitive methods (ICP-MS).
4. For minor and trace elements, the concentrations exploited and types of land-based deposits need to be checked.

Chapter 4
Characteristics and Formation Process

Yves Fouquet

Introduction

Scientific exploration carried out over the past 30 years has identified several geological and geochemical processes leading to the concentration of metals in the deep sea. These discoveries open up new prospects for the exploration and identification of ocean mineral resources. Furthermore, the mineral deposits discovered (hydrothermal sulphides, nodules and manganese crusts) are related to specifically submarine processes which have no land-based equivalent on the continental crust. According to the context and type of substrate involved, hydrothermal mineral deposits can contain high concentrations of copper, zinc, gold, silver, cobalt, lead and barium, but also rarer elements such as cadmium, antimony, cobalt, germanium, indium, selenium and mercury.

Due to the salinity of seawater and the increase in boiling point with depth, the deepest fluids have a greater capacity to transport metals. Manganese oxide nodules and crusts are of interest for their nickel, copper and cobalt concentrations, but they can also be rich in platinum, titanium, rare earths (in particular cerium), zirconium, molybdenum, vanadium, tellurium, thallium and phosphorus. All these mineral deposits are found directly on the ocean floor. When exploited, this should reduce environmental impact. Furthermore, unlike land-based mining facilities, specific facilities on board a vessel can be easily relocated. Thus, small deposits very rich in metals, which would never be exploited on land, could be of economic value.

Following a brief reminder of the mineral deposits exploited on the continental shelf, deep-sea mineral deposits will be studied, by presenting the main characteristics of their geological environment, their composition and the geochemical processes which lead to metal transport and concentration.

Y. Fouquet (✉)
Centre Bretagne, Géosciences marines,
Ifremer, BP 70, 29280 Plouzané, France
e-mail: Yves.Fouquet@ifremer.fr

Y. Fouquet, D. Lacroix (eds.), *Deep Marine Mineral Resources*,
DOI 10.1007/978-94-017-8563-1_4,

Table 4.1 Main types of submarine mineral deposits

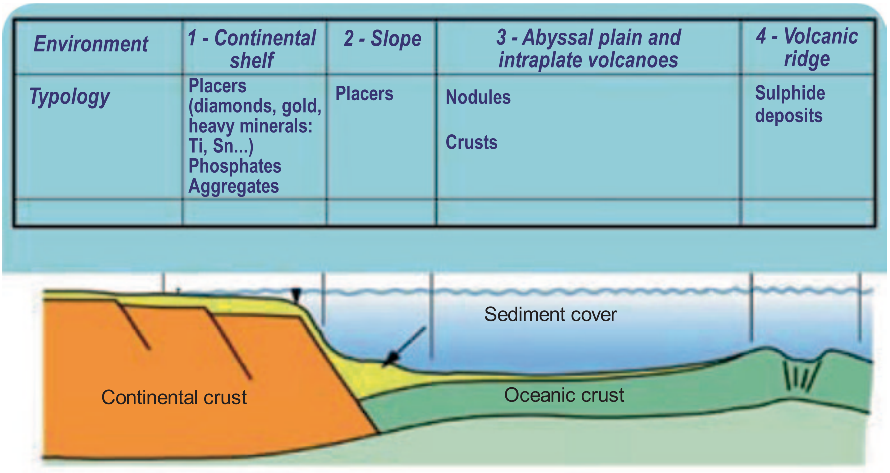
Type	Location	Exploitable raw material	Depth	Mining status	Economic value
Salt	Coastal	Salt	Inshore	Operational	Moderate
Sand and gravel	Shoreline	Sand and gravel	Shallow	Operational	High
Diamonds	Continental margin	Diamonds	<250 m	Operational	High
Marine placers	Beaches, shallow waters	Tin, gold, chromium, zirconium, rare earths, titanium	Shallow	Operational	Moderate
Phosphates	Shallow waters and former volcanoes	Phosphate	Shallow to moderate depth	Non-operational	Low
Nodules	Large abyssal plains	Copper, cobalt, nickel	4,500 to 5,500 m	Potential resources	Moderate
Manganese crust	Former intraplate volcanoes	Cobalt, copper, platinum	1,000 to 2,500 m	Potential resources	Moderate to high
Hydrothermal sulphides	Volcanic ridges	Copper, zinc, silver, gold, cobalt, lead	1,000 to 4,000 m	Potential resources	High

Shallow-Water Mineral Deposits

All mineral substances concentrated by geological processes and which could be used by man can be considered to be mineral resources. Eight main types of mineral resources are currently distinguished in the oceans (cf. Table 4.1); these groups can be divided into shallow-water mineral deposits (<200 m), which are already being mined, and deep-sea mineral deposits (<1000 m), whose potential is attracting increasing interest from mining companies (cf. Table 4.1 and Fig. 4.1). The first mineral resources exploited are located in very shallow waters on the continental shelf. Reference can be made to salt and aggregates, which constitutes a major activity of ancestral origin, with well-developed techniques. Placer deposits of heavy minerals and diamonds are also mined. Phosphates can also be concentrated in marine sediment, but are not as yet exploited.

Heavy Mineral Placers

Certain high density minerals are extracted from continental rocks during alteration processes and are transported by river to the ocean in the form of “placers” in sediment formations. These placers are found on coastal beaches and the continental shelf and are mined for tin (7% of global production), gold, platinum, titanium, chromium, zirconium and rare earths. Malaysia, the world’s largest tin producer, extracts 30% of its production from submarine placers. In Thailand and Indonesia, 50% of tin production comes from the ocean.



Environment	1 - Continental shelf	2 - Slope	3 - Abyssal plain and intraplate volcanoes	4 - Volcanic ridge
Typology	Placers (diamonds, gold, heavy minerals: Ti, Sn...) Phosphates Aggregates	Placers	Nodules Crusts	Sulphide deposits

Fig. 4.1 Location of the main types of marine mineral resources

Diamonds Diamonds extracted from continental geological formations are transported by river and found in marine sediment on the continental shelf. Diamond-bearing areas are mined off the coast of Namibia and South Africa. Diamond mining takes place at depths of up to 200 m. Since the early 1990s, the company De Beers has extracted 50 % of its production from submarine deposits.

Phosphates Remains of marine organisms accumulate in the sediment and release phosphorous, which precipitates to form phosphate "nodules". These balls grow 1 to 10 mm in a 1,000 years and reach phosphate concentrations of 12 to 18 %. Certain phosphate nodules can also be rich in uranium. These mineral deposits are formed on submarine terraces, in areas of high productivity related to the upwelling of deep waters rich in nutritive elements. They are generally found in waters less than 1,000 m deep in tropical regions. Most deposits date back to the Miocene (5 to 23 million years).

Phosphorous is an essential nutrient for all living organisms' growth. Its global annual consumption is 150 million tonnes. Known land-based reserves represent around 50 years' consumption. In 2007, an exploration license was obtained by the company Bonaparte for this type of deposit off Namibia, and prospecting began at depths of 150 to 300 m. The discovery of a sufficiently rich deposit—around 50 million tonnes of sediment containing between 10 and 15 % phosphates—would allow profitable exploitation for over 20 years.

Deep-Sea Mineral Deposits

Manganese Nodules

The positions of the main nodule fields and hydrothermal mineral deposits are indicated on the world map in Fig. 4.2. Manganese nodules are considered to be potential mineral resources. Exploitable metal concentrations (copper + nickel + cobalt) are around 1.3 % in the Pacific. Concentrations in the richest areas (up to 2.4 %) are greater than or equal to those of land-based deposits. Growing awareness of the potential economic importance of nodules caused President Johnson in 1966 to call for the seabed to be declared "common heritage of mankind". This proposal was made into a resolution in 1970 by the United Nations General Assembly. As copper resources, nodules represent around 10 % of continental reserves and underwent many investigations in the 1970s and 1980s. These investigations did not lead to their exploitation for various reasons: poor estimation of the resource, high cost of metal processing, political issues related to the law of the sea and drop in metal prices. These nodules constitute however a major potential reserve of nickel, copper and cobalt, which would help to diversify supply sources in case of tension over continental resources.

Their exploitation would require high resolution maps to be produced, the formation processes for the richest nodules to be understood and the biodiversity and functioning of related ecosystems to be well known, in order to minimise the environmental impact of their possible exploitation. With this in mind, France has obtained two mining licenses in the North Pacific.

Location The first nodules were discovered in shallow waters in the Kara Sea in 1868. Then, between 1873 and 1876, the British vessel *Challenger* showed that nodules were common in the deep sea. Their mining potential has been highlighted since the 1950s due to nickel contents greater than or equal to those of laterite deposits, copper contents greater than or equal to those of major land-based copper deposits (0.5 % copper) and cobalt concentrations similar to those of land-based deposits. Currently, nodules are known to exist in all the oceans, at all latitudes and even in some lakes. Nevertheless, metal abundance and wealth on the seabed vary tremendously. From 1973, particularly rich fields with a high density of nodules were found along an east-west belt in the North Pacific in the Clarion-Clipperton Zone (Fig. 4.2).

The sediment environment of nodules is composed of deep-sea red clay, siliceous radiolarian ooze, or carbonate foraminiferal ooze. These sediments are always heavily water-saturated. In the Clarion-Clipperton Zone, ooze is composed of radiolarians (30 %) and iron and manganese hydroxide. These sediments lie on a volcanic crust formed on the axis of the East Pacific Rise some 30 to 40 million years ago. The mountainous features, 100 to 300 m high and spreading north-south over several dozen kilometres, were inherited from the East Pacific Rise. The faults affecting the sediments are located in line with the faults of the basaltic basement. The topography in parallel ridges and valleys inherited from the rise is essential for nodule formation. It enables secondary displacement of sediment particles by

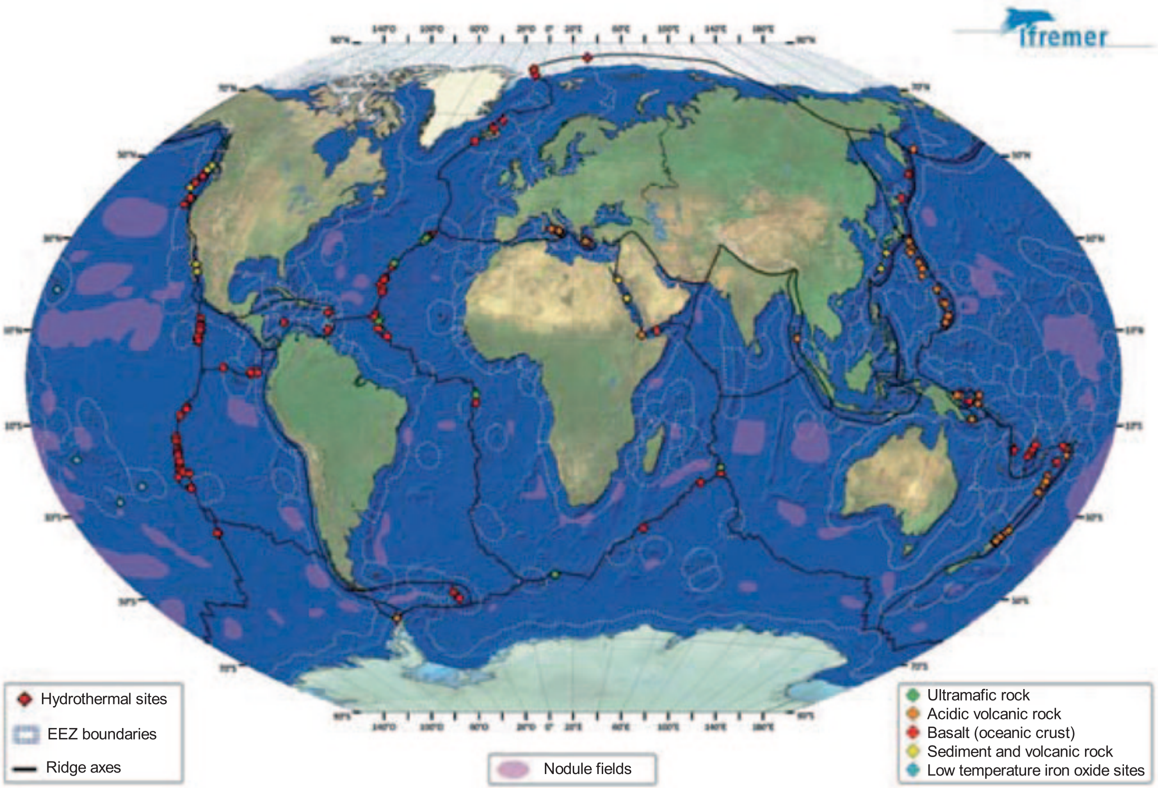


Fig. 4.2 Map showing the main nodule fields and hydrothermal sites in the deep sea

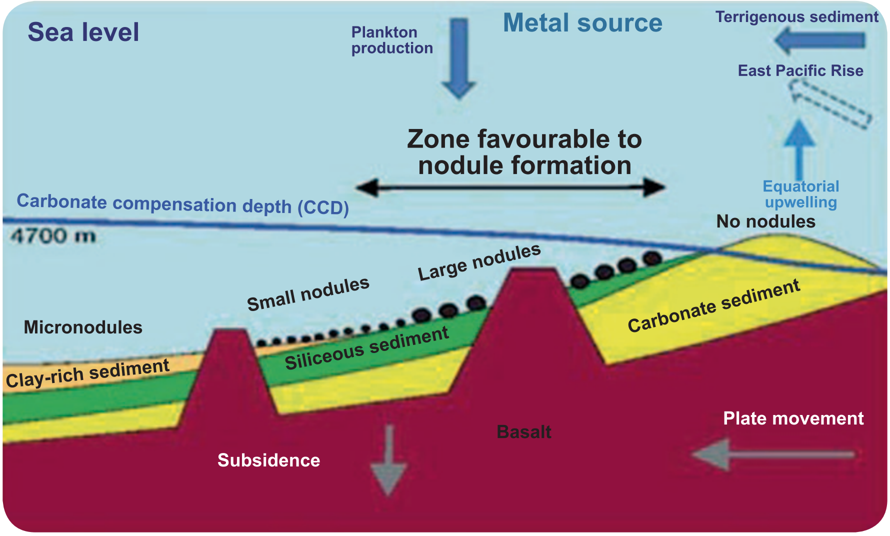


Fig. 4.3 Diagram illustrating favourable conditions for nodule formation

gravity and current phenomena, leading to the local generation of areas with low sedimentation rates in which nodules can form. This results in a discontinuous regional distribution of nodule fields extending over a few kilometres, within which nodule facies vary laterally.

Formation Mechanism Sediments in nodule areas are accumulated very slowly (3–10 mm per 1,000 years) and are composed of dust of continental origin and skeletons of planktonic organisms (radiolarian ooze). There exists an optimal sedimentation rate for nodule formation: at less than 2 mm in a 1,000 years, only hydrogenated crusts form, while at over 10 mm in a 1,000 years, the seabed becomes sediment, and nodule formation mechanisms can no longer take place. Radiochronological dating methods have shown nodule growth rates of a few millimetres per million years. This growth rate, which is considerably lower than the sedimentation rate, raises the problem of maintaining nodules at the sediment surface. For some samples, variations in growth rate have been observed in relation to climate variations, with growth possibly stopping during glacial periods.

Four chemical sources of particulate or dissolved elements were considered for nodule formation: planktonic organisms, continental input from rivers, hydrothermal vents and volcanic dust. Manganese's residence time in seawater, evaluated from input from rivers and its concentration in seawater, has been estimated at around a 100 years, while that of nickel and copper is closer to a 1,000 years. Cobalt's residence time, on the other hand, is only around 10 years. The precipitation of manganese and iron in seawater is an ordinary process that occurs at all latitudes and all depths. However, nodules are only found in a small part of the ocean floor, at depths of over 4,000 m, in areas where carbonates can dissolve due to greater acidity of deep waters, caused by greater solubility of CO_2 with pressure (Fig. 4.3).

Recent studies have shown that the formation of nodules is independent of active volcanic activity. However, it is worth emphasising the importance of all levels of life for nodule genesis. The quantity of elements required for their formation is easily made available by the dissolution of planktonic organisms which accumulate in the sediment. There is a link between surface plankton productivity and nodule formation on the seabed. The richest nodules are associated with the dissolution of tests of siliceous organisms. The quantity of available organic matter also determines the amount of benthic life and therefore the degree of bioturbation. Fragments of organisms often act as a nucleus for nodule formation. Furthermore, through their involvement in redox processes, micro-organisms doubtlessly play an important role in the test dissolution process then in the precipitation of the metals concentrated in nodules. Ultimately, there are not several nodule growth phenomena, but rather nodules with different geological histories. The question of the maintenance of surface nodules, raised by the fact that their growth rate is a thousand times lower than the sedimentation rate (a few millimetres per 1000 years), is not entirely resolved. It is estimated that the proportion of nodules buried in the top metre of sediment is equal to that of surface nodules. Active bioturbation causes small nodules to be relocated. Periodic variations in currents connected to climate variations can also periodically erode the sediment around nodules. In short, current models involve an exclusively sedimentary origin of nodules. Life, lithospheric plate dynamics and global climate variations play a fundamental role in their genesis.

Composition Polymetallic nodules form dark-coloured balls, 5 to 10 cm in diameter, containing around 40 % water (Photo 13). They are mainly composed of manganese and iron hydroxides (Table 4.2). The most crystallised layers are the richest in nickel and copper, which do not form specific minerals, but are incorporated in the crystalline networks of manganese and iron oxides. In the nodules in the Pacific, the average concentrations are 0.42 % copper, 0.63 % nickel, 0.24 % cobalt and 18.50 % manganese. The Clarion-Clipperton Zone, for which many mining licenses have been allocated, is particularly rich in copper (0.82 %), nickel (1.28 %) and manganese (25.40 %). Recent estimations for this zone show that, for a surface area of around 9 million square kilometres (i.e. 15 % of the Pacific Ocean floor at depths of between 4,000 and 5,000 m), nodules weigh an estimated 34×10^9 tonnes, including 7.5 billion tonnes of manganese, 340 million tonnes of nickel, 275 million tonnes of copper and 78 million tonnes of cobalt. Recent data obtained by submersibles show heterogeneous distributions which require rigorous mapping and sampling efforts in order to accurately select the most favourable areas for exploitation. One of the main problems posed by nodule mining is the environmental impact of their extraction over considerable areas.

Over and above base metals (Cu, Ni, Co), nodules contain rare earths whose economic importance is growing for cutting edge technologies (electronics) and technologies related to the development of green energy (electric motors, new generation photovoltaic cells …).

Two major morphological types are distinguished, smooth surface nodules of purely hydrogenetic origin, i.e. generated from elements contained in seawater, and

Table 4.2 Average compositions of the main types of deep-sea mineral deposits for the main environments in which they are formed (from Y. Fouquet 2009)

	Nodules		Crusts		Hydrothermal sulphides		
	Clipperton	Pacific	Pacific	Polynesia	SW pacific	East pacific	Atlantic
%							
Iron	6.90	12.70	15.99	15.08	11.22	25.45	27.64
Mn	25.40	18.50	21.95	19.48	0.18	0.05	0.04
Copper	0.82	0.42	0.09	0.27	3.48	3.85	8.49
Zinc	0.14	0.09	0.07	0.06	16.28	10.46	6.64
Cobalt	0.24	0.24	0.69	0.79	0.00	0.04	0.11
Nickel	1.28	0.63	0.41	0.38	0.00	0.00	0.02
Titanium	0.53	0.78	1.20	0.93	–	–	–
Sulphur	–	–	–	–	21.46	33.34	31.59
Barium	0.28	0.20	0.18	0.14	12.19	1.99	3.35
Silica	7.60	8.80	4.14	2.40	14.84	11.48	8.24
Grams/tonne							
Lead	450	820	1626	1163	14493	1180	450
Platinum	0.10	0.10	0.64	1.05	–	–	–
Gold	–	–	–	–	2.44	0.61	3.40
Silver	<0.2	<0.2	<0.2	<10	404	115	81
Arsenic	159	159	272	248	1484	351	211
Cerium	530	530	1605	702	–	–	–
Molybdenum	520	360	442	307	132	103	55
Zirconium	350	620	618	484	–	–	–

diagenetic nodules, with a rough surface, generated from elements contained in manganese-rich sediment. The first type, which lie on the sediment, are low in manganese ($Mn/Fe < 2.5$) while the second, partially buried in the sediment, are high in manganese ($Mn/Fe > 4$). Certain intermediate types have a smooth upper surface of hydrogenetic origin and a rough lower surface of diagenetic origin. When cross-sectioned, nodules appear to be formed of concentric layers illustrating their growth. The core is often composed of former nodules, rocky fragments (basalt, limestone), animal remains and sometimes shark teeth.

Cobalt-Rich Crusts

Location Ferromanganese oxide crusts have been identified in all the oceans (Fig. 4.4) in environments where the combination of currents and low sedimentation rates has prevented sediment deposit for tens of millions of years. In general, they are associated with intraplate submarine elevations, isolated seamounts and volcanic chains. These crusts range from a few centimetres to 25 cm in thickness and cover surface areas of several square kilometres. They are generally deposited

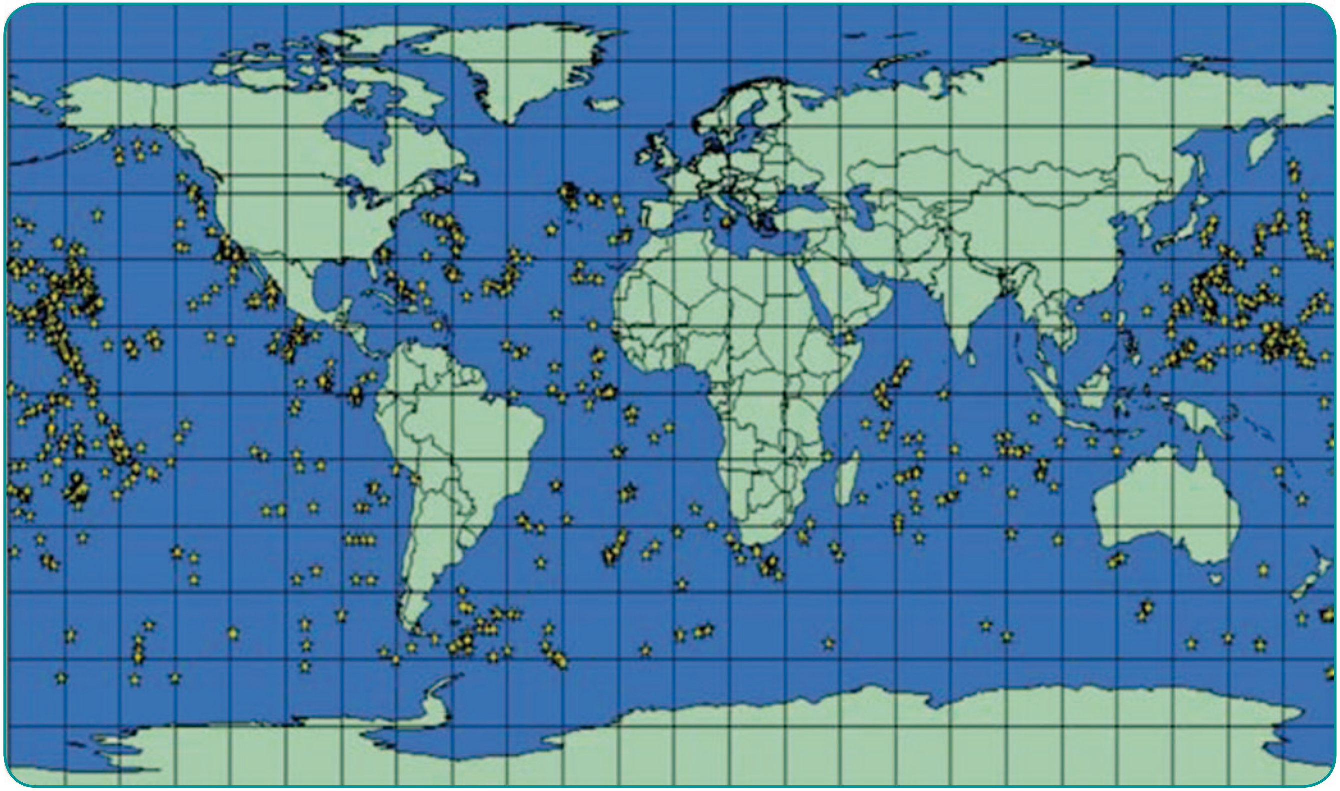


Fig. 4.4 Distribution of manganese crusts in the oceans

on indurated substrata (submarine volcanoes, former underwater atolls) at depths ranging from 400 to 4,000 m. Estimations indicate that the total surface area covered by crusts is around 6.35 million square kilometres, i.e. 1.7 % of the ocean surface area.

A very small number of underwater volcanoes (of an estimated 50,000) have been studied in the Pacific Ocean. Cobalt- and platinum-rich deposits have the greatest economic potential and are all located in the Pacific Ocean. On the scale of this ocean, the deposits with the highest cobalt contents are in Polynesia (Fig. 4.6). They appear in the form of, sometimes continuous, crusts, on the outer edges of submarine plateaus (e.g. Tuamotu) and on volcanoes at depths of between 800 and 2,500 m.

Formation Mechanism Manganese concretions are formed from the precipitation of Fe++ and Mn++ from seawater in the form of iron oxide-hydroxide (Fe_2O_3) and manganese oxide-hydroxide (MnO_2) (Fig. 4.5). Growth rates are extremely slow, around 1 to 6 mm per million years. This is why the thickest crusts can be up to 60 million years old. This very slow growth rate means that this phenomenon is effective and leads to high concentrations of several metals, such as cobalt and platinum. The phenomenon is reinforced when the oxygen content in seawater is minimal. Thus, fluctuations in platinum content could reflect the passage through the oxygen minimum zone in the seawater column. High platinum concentrations have been interpreted, on other sites, in terms of the oxidation of divalent platinum present in seawater in the form of a chlorine complex, to form tetravalent platinum trapped in iron-manganese oxides. Precipitation processes are probably also influenced and reinforced by bacterial activity. These hypotheses need to be discussed based on more accurate field data.

Microspheroids of cosmic origin are frequent in some areas. These metal micrometeorites contain nickel, cobalt and platinum group metals in substantial quantities. Rough calculations nevertheless show that these micrometeorites do not answer for the high cobalt and platinum concentrations of these crusts.

Composition Like nodules, crusts are mainly composed of iron and manganese oxides. They are however on average three times higher in cobalt and often have high platinum concentrations. Crusts are among the richest sources of cobalt known on earth. These crusts could constitute the first cobalt ore, as this metal is to date a by-product of other mining processes. Crusts in Polynesia's EEZ have far higher cobalt (1.8 %) and platinum (3.5 grams per tonne) concentrations than those of other ocean areas (Co = 0.25 %). Cobalt concentrations are far higher than in lateritic ores mined on land where the content rarely exceeds over 0.1 to 0.2 % (Fig. 4.6). On certain sites that are very rich in platinum, this could be a non-negligible by-product. Cobalt is mainly used to make special steels. The importance of this metal is renewed due to high demand for cobalt (production doubled between 1999 and 2006) for new technologies, in particular alloys for aviation and batteries. Around a third of production is used in the aerospace industry. The importance of platinum is also renewed by industry's demand for catalysts (exhaust pipes and fuel cells).

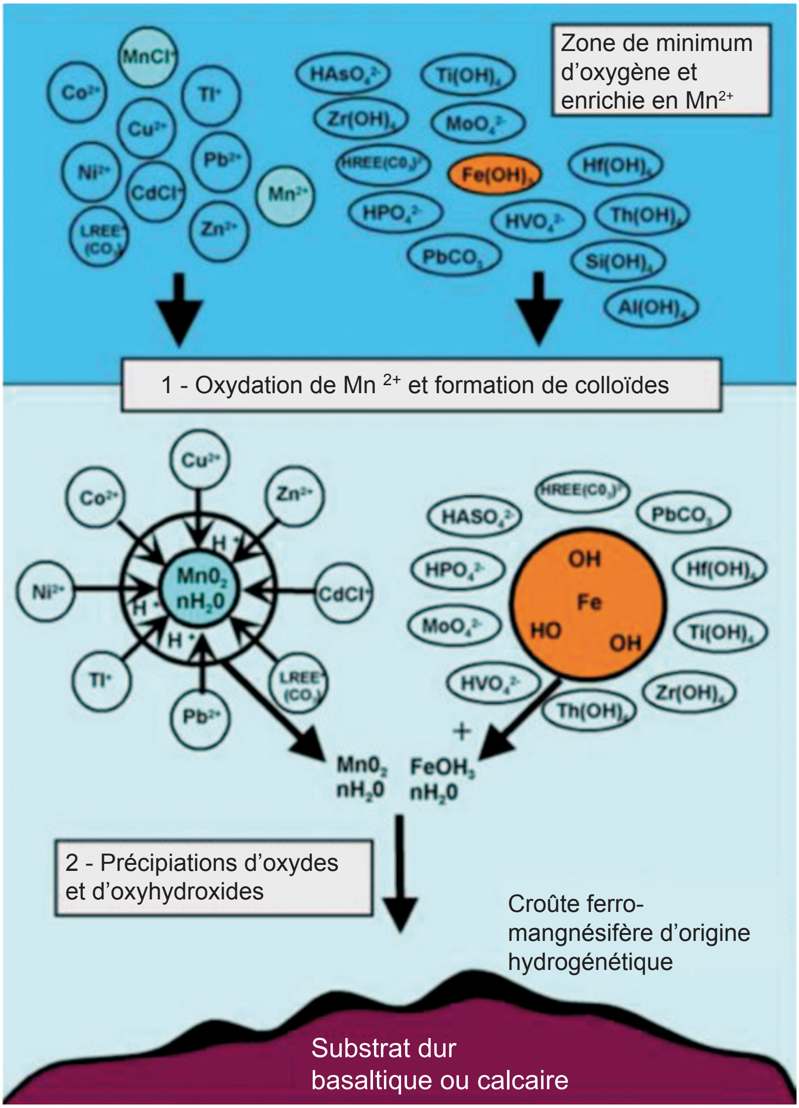


Fig. 4.5 Diagram illustrating the genesis of hydrogenetic crusts through the formation of complexes and colloidal phases facilitating the absorption of metals

In addition to cobalt, manganese crusts are a potential source of many other metal elements such as titanium, nickel, rare earths (in particular cerium), zirconium, molybdenum, vanadium, tellurium, thallium and phosphorus.

Over and above the academic interest of these data, it is justifiable to attempt to determine the economic potential. Estimations show that a potentially economic site should have cobalt concentrations of over 1 % and platinum concentrations of

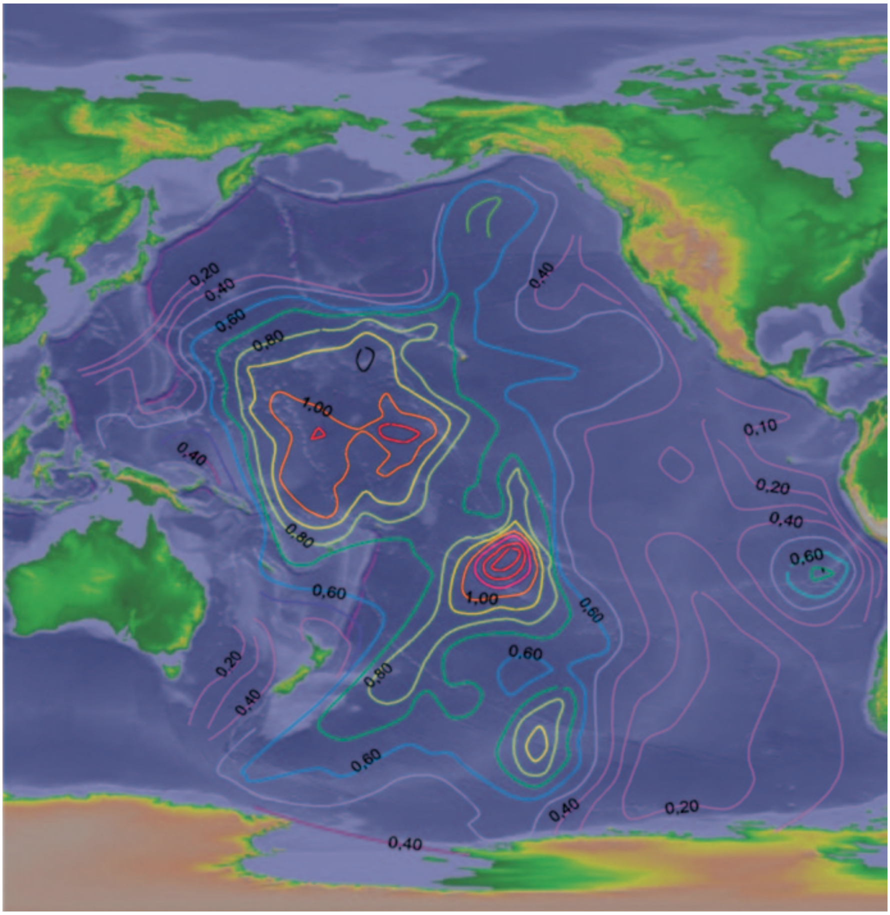


Fig. 4.6 Map of cobalt concentrations in manganese-rich crusts in the Pacific

over 1.5 gm per tonne in crusts at least five centimetres thick. Deposits should of course have a certain continuity over relatively flat surfaces.

A proper evaluation of the economic potential of these mineral deposits will only be feasible once field data will be able to determine the parameters required for accurate calculations: geological controls in rich areas, deposit continuity, influence of substratum on dilution upon pick-up. An important point concerns the study of seabed roughness, in order to determine the richest, flattest and most continuous areas in which crust mining would be possible without the crusts being diluted in too great a volume of sterile substrate. Such cobalt-rich areas are known in the Tuamotu Islands area where crusts form a flat, continuous surface on indurated sediment formations. From a scientific point of view, efforts remain necessary to more fully understand the rules of distribution, variability in thickness and composition, and geological and chemical parameters governing the formation of the richest accumulations. To date, no field study using a manned submersible or remote-operated underwater vehicle has been carried out on this type of deposit in the ocean.

Hydrothermal Polymetallic Sulphides

Submarine hydrothermal activity is a consequence of plate tectonics and volcanic activity. These processes generate the oceanic crust at divergent boundaries that form the 60,000 km of mid-ocean ridges. Quantitative estimations show that the quantity of seawater that flows through ocean rocks is around 1.3 to 9×10^{11} tonnes a year, evacuating 36 to 44×10^{18} calories a year of heat energy. These figures represent the equivalent of the flow of the total mass of ocean waters through hydrothermal systems every 5 to 11 million years. This is therefore a major phenomenon on a global scale. According to these calculations, since the formation of the oceans, around 4 billion years ago, all the water of the oceans has flowed through the oceanic crust several hundred times.

This hydrothermal activity is an important metal transport and concentration mechanism, causing metals to accumulate in the form of sulphide deposits. This type of ore is well known in fossil deposits mined on land and formed below the sea over geological periods. A portion of the copper, zinc, silver and gold mined on land is produced from this type of deposit, some of which also contain cobalt and barium. For instance, over 30 % of silver resources mined on land come from fossil sulphide deposits formed below the sea during geological periods.

The first deposits observed only represented a few tens of thousands of tonnes of polymetallic sulphides. Today, several hydrothermal fields are known whose dimensions and mineral contents are similar to land-based mines, i.e. several million to tens of millions of tonnes.

Location The first hydrothermal mineral deposits associated with hot brine (70 °C) were observed in 1962 in the Red Sea Rift. The first black smokers (350 °C) were discovered on the East Pacific Rise in 1978, at a depth of nearly 3,000 m. After 30 years of exploration in all the world's oceans, the discovery of nearly150 hydrothermal sites (Fig. 1.4) demonstrates the importance of metal extraction, transport and concentration processes related to submarine volcanic activity. Sulphide mineral deposits are now known to exist at depths of between 800 and 5,000 m. Through exploration, hydrothermal activity has been discovered and its diversity specified in varying geodynamic contexts. Volcanic areas in which hydrothermal activity is found can be divided into four types of environments: fast-spreading ridges, slow-spreading ridges, back-arc basins and intraplate volcanoes. So-called slow-spreading ridges, such as the Mid-Atlantic Ridge, spread at rates of no more than two centimetres a year, while fast-spreading ridges spread at rates of up to 18 cm a year in the south of the East Pacific Rise, north of Easter Island.

Fast-Spreading Ridges: Many Small, Unstable Hydrothermal Fields The first black smokers were discovered in 1978, on the East Pacific Rise, at the latitude of Mexico at 21 °N. Certain researchers predicted that activity would be particularly intense further south, on the fastest-spreading portion of the ridge (spread: 17 cm a year), between latitudes 15 and 20 °S. Numerous campaigns were carried out in the 1980s and 1990s, in particular by American, French and German teams. Many discoveries were made along the ridge, from Mexico to Easter Island: 13 °N, 11 °N, 9 °50' N, 17 °30' S, 18 °15' S, 18 °30' S, 21 °30' S … (Fig. 4.2). During a single campaign with the Nautile submersible, 70 hydrothermal sites were discovered between 17 and 19 °S, on the world's fastest-spreading ridge. This demonstrated that the degree of activity depends on the spreading rate.

However, the number as well as the very small size (a few hundred square metres) of the hydrothermal fields indicates that these are extremely unstable systems, due to the frequency of tectonic movements and the high number of volcanic eruptions. This configuration is incompatible with the formation of mineral accumulations of economic importance. Sulphide concentrations at the axis are insignificant in terms of mineral resources. The only high volume deposits on fast-spreading ridges are located on volcanoes a few kilometres away from the ridge's axis; thanks to the high degree of stability of these hydrothermal systems over a few thousand years, several million tonnes of sulphide clusters have been able to form on these volcanoes.

Slow-Spreading Ridges: Few Yet Vast Hydrothermal Sites For several years, it was believed that black smokers did not exist on slow-spreading ridges, such as the Mid-Atlantic Ridge. Magma chambers, more local and deeper, were thought not to allow the hottest fluids to reach the surface. In 1985, the discovery, just a few months apart, of two fields of black smokers at 26 °N and 23 °N on the Mid-Atlantic Ridge showed that hot hydrothermal activity was a general phenomenon on ridges, whatever their spread rate. Since then, many discoveries have been made, and around fifteen sulphide sites are now known along the Mid-Atlantic Ridge (Fig. 4.7). Age measurements taken on the TAG site at 26 °N show that several successive episodes of activity occurred over a period of around 40,000 years. This figure is taken in comparison with the duration of a few dozen years, which is the general rule on the axis of fast-spreading ridges.

The combination of thermal and topographical effects focuses hydrothermal convections on high, hot spots of volcanic segments (for instance the Lucky Strike site). However, as sites are known at the base and summit of the walls of the axial rift, their position is therefore controlled not by volcanic activity, but by tectonics. Other sites are located at segment extremities (Rainbow, Saldanha and MenezHom), in contexts in which the low surface magmatic productivity lets mantle rocks show through. These discoveries considerably extend the potential scope of investigation, as now not only volcanic summits are to be explored, but also the base and summit of rift walls; they also show that the volumes of sulphides at slow-spreading ridges are higher than those of fast-spreading ridges.

Sediment-Covered Ridges A specific case concerns the portions of sediment-covered ridges, due to proximity with continents. In these environments, hydrothermal convective flows successively affect the basaltic rock of the oceanic crust, then

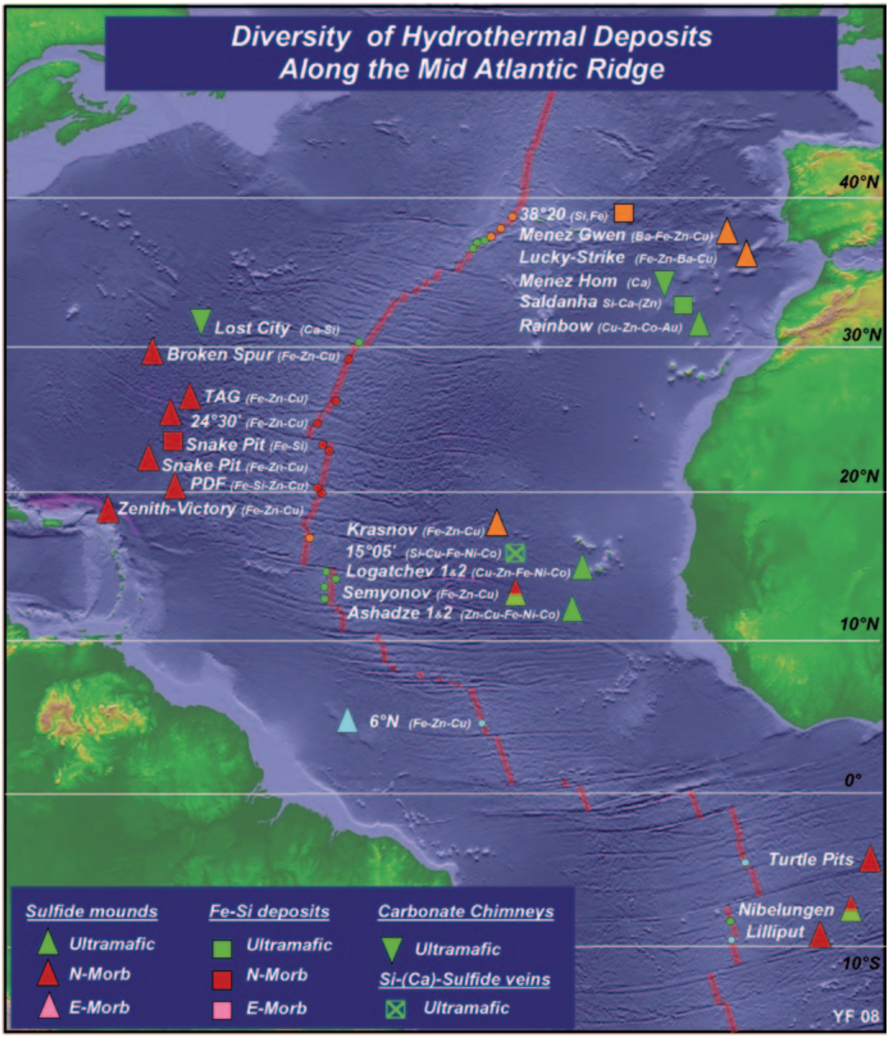
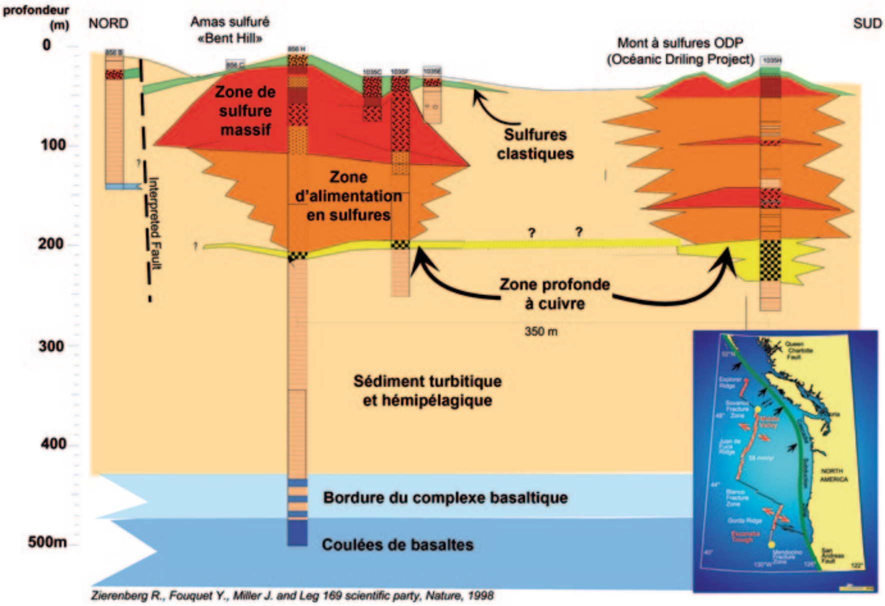


Fig. 4.7 Hydrothermal sites along the North Atlantic Ridge (Fouquet et al., 2010)

the sediments that act as a screen and trap for metals. The Ocean Drilling Program (ODP) in 1996 (LEG-ODP 169) demonstrated the importance of these traps for the formation of sulphide deposits (Fig. 4.8). This drilling campaign revealed one of the largest deposits currently known in the oceans. Estimations, obtained by three-dimensional sampling, reached almost 15 million tonnes of mineral ore, particularly rich in copper and zinc. The programme also demonstrated that a large share of mineral deposits do not form at the surface but deeper down.



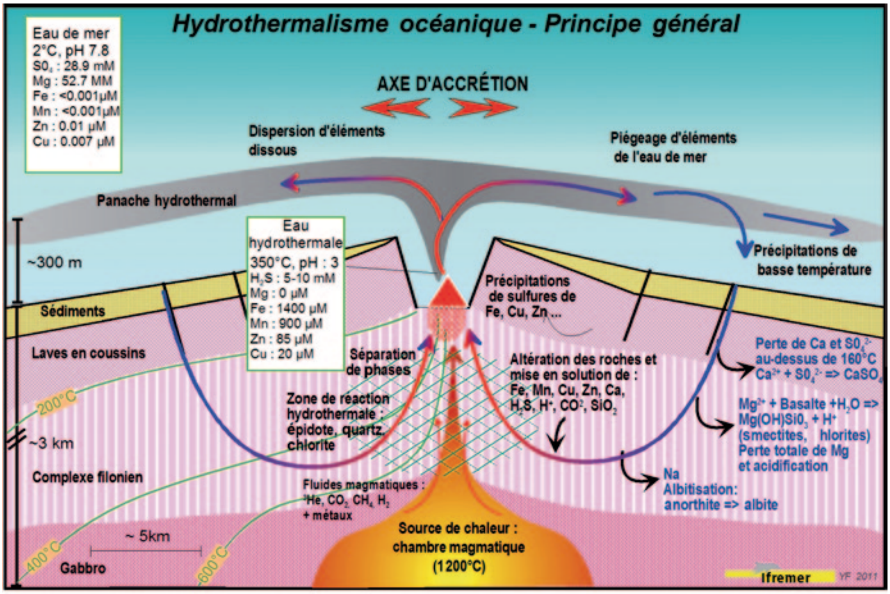
Zierenberg R., Fouquet Y., Miller J. and Leg 169 scientific party, Nature, 1998

Fig. 4.8 Cross-section of the Middle Valley sulphide deposits (Juan de Fuca Ridge) formed on a sediment-covered ridge (Zierenberg et al. 1996)

Back-Arc Basins and Volcanic Arcs Behind Large Oceanic Trenches Contrary to ridges, which are the place where the oceanic crust is formed, volcanic back-arc basins form in environments where plates are destroyed (subduction zones). In the late 1980s, back-arc basins, behind oceanic trenches, attracted the attention of metallogenists, due to the fact that the great majority of fossil deposits mined on land are formed in this type of context. Due to their location close to continents, they are preferentially incorporated into continents during plate collisions.

Back-arc basins can be considered as small volcanic ridges formed behind large oceanic trenches. Seawater injection at lithospheric plate downwelling areas (subduction zones) causes rocks' melting point to fall. Consequently, the pockets of lava formed supply volcanic islands (volcanic arc), forming chains behind and parallel to the trench. Tonga and the Mariana Islands are examples of islands formed by this process. These contexts are favourable to the installation of hydrothermal convection cells and are home to several hydrothermal fields.

Back-arc basins' major instability, as well as the high variability in the nature of the volcanic rocks associated with them, have led to the discovery of extremely varied hydrothermal sites in terms of the composition of fluids and associated mineral deposits. These basins are classified according to their degree of maturity. Young basins can open up in the continental crust (Okinawa Trough) or island arc crust (Lau Basin, Manus Basin). In the latter case, the influence of melted products from the subduction zone is reflected in the composition of associated hydrothermal deposits. The impact of global phenomena, such as subduction, in local phenomena



Principe général de la convection hydrothermale sur une coupe transversale d'une dorsale rapide.
Noter le fort enrichissement en métaux dans le fluide hydrothermal par rapport à l'eau de mer.

Fig. 4.9 General principle of hydrothermal convection

and the formation of mineral deposits can thus be observed. The most developed basins are comparable to small ridges on which basalt is dominant and mineralisation processes are very close to those of ridges. In the youngest basins located near the active volcanic arc, the dominant volcanic rocks are andesite and rhyolite, which are inexistent on ridges.

Formation Mechanism

Hydrothermal sulphide deposits result from the circulation of seawater through the oceanic crust under the effect of high thermal gradients (Fig. 4.9). They are found on all submarine structures of volcanic origin. According to their location, they show great diversity, both in terms of the physical and geological characteristics of deposits and the metals that can be mined. These differences are controlled by physical processes (e.g. variation in boiling point according to depth) and by the type of rocks through which the hydrothermal fluids circulate (various volcanic rocks, mantle rocks, sediments).

Despite the diversity of systems, the main components of a hydrothermal system can be summarised in a simple diagram (Fig. 4.9). The melted lava at 1,200 °C contained within the magma chamber forms lava flows on the ocean floor. The position of the magma chamber, situated only a few kilometres deep, creates a thermal

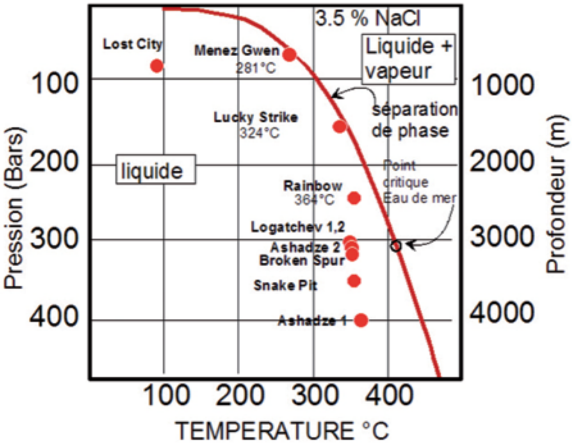


Fig. 4.10 Boiling curve of seawater according to pressure and temperature

gradient of several hundred degrees per kilometre. Seawater, which is cold and low in metals, penetrates along faults and cracks formed by divergent plates and is greatly heated as it approaches the magma chamber. As soon as the temperature exceeds 160 °C, calcium sulphate precipitates in the form of anhydrite ($CaSO_4$). Seawater sulphates are also reduced to the form of hydrogen sulphide which remains in solution. Intense reactions lead to strong weathering of the rocks through which circulation occurs and result in a total loss of magnesium which is incorporated in newly formed minerals.

One of the consequences of these reactions is acidification of the fluid, increasing its capacity to dissolve the metals contained in rocks. The high salinity of seawater also facilitates the dissolution of metals to form chloride complex solutions. This generates acidic, reduced, hot (350 °C) fluids, devoid of magnesium and with high metal contents. The low density of these fluids causes their upwelling and induces hydrothermal convection which emerges in the form of hot vents in the most recent fissures in the ridge. Sulphide deposits are formed on the ocean floor when these hydrothermal fluids (350 °C) are rapidly cooled upon contact with seawater (2 °C).

Due to the increase in phase separation temperature (boiling point) with pressure, the deepest fluids have a greater capacity to transport metals. At a depth of 3,000 m (300 bars), the phase separation temperature is close to 400 °C (Fig. 4.10).

A group of around ten black smokers 2 cm in diameter, emitting a fluid containing 100 ppm of metals at a rate of 2 m/s, produces 250 tonnes of metal sulphides per year. An active field can contain around fifty of these smokers and the field's lifetime can be several tens of thousands of years. In such a system, around 1.5 million tonnes of sulphides (mainly iron sulphides) can be produced every hundred years. It is however estimated that 95 % of metals are dispersed in seawater. An efficient trap and specific geological configurations are therefore required to retain a higher proportion of metals.

When systems are stable, mounds of polymetallic sulphide, exceeding 70 m high and a few centimetres in diameter, are formed. These sulphide deposits may total several million to tens of millions of tonnes. The volumes, weights and concentrations of exploitable elements from such deposits are identical to those of many land-based mines. The surface of the mounds consists of scree of broken chimneys cemented by subsequent hydrothermal circulation; they are topped with a complex of active chimneys over an area of tens of square meters. On some sites, deposits are organised in and around depressions forming the crater of the volcano. Mounds are formed by the accumulation of broken chimneys at the surface, but also by internal precipitation of minerals, and by replacing the underlying bedrock. The end result is an accumulation of massive sulphides.

Chemical Composition

The composition of hydrothermal sulphide deposits can vary considerably according to the geodynamic environment, the nature of basement rocks affected by hydrothermal circulation, the water depth, the phase separation processes and the maturity of deposits. The main factor is the nature of the basement rocks and of metals that are pre-concentrated before their extraction by hydrothermal circulation. Thus, even although the general principle of hydrothermal circulation applies to all sites, there are considerable differences in the compositions of deposits. In general, compared to nodules and manganese crusts, these ores have a high potential since the total of copper + zinc often exceeds 10 %. It is very high (20 %) in back-arc basins and around 15 % on slow (Atlantic) and fast (East Pacific) spreading ridges. Furthermore, most sites are also highly enriched in silver and often gold. Some specific sites in the Atlantic associated with mantle rocks are also enriched in cobalt. It should be noted however that these estimations are based on two-dimensional sampling carried out from submersibles. A real estimation in the economic sense of the term would require the vertical variations in composition to be known, for which drilling must be carried out; we know however that, in fossil deposits, deep areas are generally the richest in copper. This point has been confirmed on the Middle Valley site, at the base of which a deep copper zone is found, mainly composed of copper sulphide.

Seawater/Basalt Interaction (Deposits Rich in Cu, Zn, Ag) This is the most common type. It is found on fast-spreading ridges and on some slow-spreading ridges and back-arc basins. Hydrothermal reactions occur in basalt. The deposits are mainly composed of iron, zinc and copper sulphides. Compositions of sulphides vary little from one site to another. However, depending on the depth and boiling phenomena, the composition of fluids may vary considerably. Salinities lower than seawater correspond to the condensation of the vapour phase produced during phase separation, while fluids more saline than seawater correspond to the salt concentration in residual brines. Metals tend to concentrate in brine phases. The youngest and most immature deposits at the ridge axis (in particular on fast-spreading ridges) are enriched in zinc and silver, while older deposits, generally outside of the axis, are enriched in copper, with zinc being mainly concentrated at the summit and at the surface of deposits. Some elements such as selenium and cobalt are enriched at certain sites.

Seawater/Basalt/Sediment Interaction (Deposits Rich in Cu, Zn, Pb, As) In certain environments, such as the Gulf of California and the west coast of Canada, the ridge is close to continents and can be buried under a layer of sediment. Hydrothermal fluids must therefore make their way through the sediment, before emerging on the ocean floor. As they rise, their acidity, which is extremely high to begin with, is neutralised by reaction with carbonates. Certain elements, such as lead and arsenic, which are enriched in sediments of continental origin, are dissolved through chemical reactions. A share of the other metals is deposited in the sediment, which acts as an efficient trap. These environments are enriched in lead and arsenic, in relation to sites formed directly on basalt.

Seawater/Andesite-Rhyolite Interaction (Deposits Rich in Zn, Cu, Pb, As, Ag, Au) In back-arc basins, acidic volcanic rocks (andesite, rhyolite) are commonly found. These environments are well known in the Western Pacific. Deposit compositions are midway between those of ridges and those formed within the context of the continental crust. In particular, samples taken from the surface are extremely high in zinc and rich in lead and arsenic in relation to sites associated with basalt. This high zinc content is also visible in the composition of fluids. One particularity of these sites is their high silver and gold contents, whose average concentrations can exceed 10 gm per tonne for gold and 250 gm per tonne for silver.

Seawater/Basalt/Mantle Rock Interaction (Deposits Rich in Cu, Zn, Co, Au) Since the late 1990s, many observations have shown that at slow-spreading ridges, the Earth's mantle is commonly exposed. On certain portions of the ridge, in particular at the ends of volcanic segments, very few basaltic flows are observed. As plates continue to relentlessly spread and diverge, the crack formed results in the exposure of subjacent rocks, i.e. mantle rocks. On the Mid-Atlantic Ridge, five active sites, Rainbow, Logatchev 1 and 2, and Ashadze 1 and 2, are currently known on mantle bedrock. They result from the reaction between seawater and ultramafic mantle rocks. Associated fluids are exceptional in terms of their high methane and hydrogen concentrations, formed by chemical reactions related to mantle rock hydration. These reactions result in a 30% increase in rock volume. In this case, the nature of the bedrock is very marked in the chemical composition of fluids and hydrothermal precipitates. In particular, sulphides are characterised by high copper, zinc and cobalt contents. Locally, gold concentrations of over 50 gm per tonne have been measured. Here, like in back-arc basins, high copper concentrations lie directly on the ocean floor at the surface of the deposits.

A Specific Case, Metalliferous Sediments in The Red Sea Metalliferous sediments in the Red Sea today constitute the largest hydrothermal mineral deposit in the world's oceans. The Red Sea is an ocean in the early stages of ocean opening; the basins are located in the deepest part of the volcanic axis. In1948, the Swedish research vessel, *Albatross*, identified abnormal temperature and salinity in the Red Sea. The first metalliferous sediments were discovered in the 1960s in several

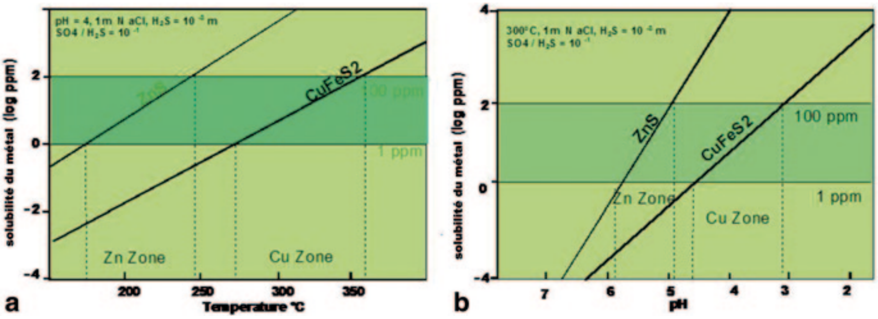


Fig. 4.11 Solubility of chalcopyrite (CuFeS2) and sphalerite (ZnS) according to temperature and pH (Large et al. 1989; Hannington et al. 1985)

basins filled with hot (60 °C) brine on the Red Sea axis. In 1969, two industrial companies (Preussag and IGS) conducted exploration to estimate the volumes of the deposits and to understand the formation process in various basins (18 are currently known). The largest basin, "Atlantis II Deep", covers about 60 km^2 at a depth of 2,000 m. In this basin, metalliferous sediments are up to 30 m thick under a 180 m layer of brine; they represent 94 million tonnes of ore containing 1.7 million tonnes of zinc, 0.4 million tonnes of copper and 4,000 tonnes of silver. In May/June 1979, the first pumping tests were performed from a vessel drilling in deep water. More recently (summer 2010), a mining permit was granted.

Chemical Zonation of Deposits

During the reaction between seawater and rocks in the crust or mantle, many metals are extracted from these rocks. Their transport in fluids is facilitated by the presence of sulphur and chlorine, with which the metals form soluble complexes. Because high pressure prevents the fluid from boiling, these transport capacities are strengthened. For instance, in typical submarine hydrothermal conditions, copper cannot remain in solution below 300 °C. Zinc precipitates between 100 and 250 °C. Hydrothermal fluids contain between 1 and 100 ppm of copper and zinc. They will precipitate chalcopyrite at between 350 and 270 °C while zinc will precipitate at between 250 and 175 °C (Fig. 4.11, graph A). These chemical characteristics specific to each element cause metals to be distributed in chimneys and sulphide mounds according to temperature and pH gradients (Fig. 4.11, graph B). Copper will be found in the core (hot) while zinc will be concentrated on the outside (cold). Thus, the zonation of mounds and chimneys is temperature-dependent and involves the replacement of early low temperature zinc-rich assemblages with copper-rich assemblages. Other metals follow these two major families of elements: cobalt, nickel, selenium and indium are preferentially associated with copper whereas cadmium, lead, arsenic, antimony and germanium are associated with zinc. Gold shows more complex behaviour and may be associated with either copper or zinc.

Industrial Interest and Geopolitical Challenges

The inventoried deposits are at different stages in terms of scientific knowledge. Given that only a small percentage of the deep sea has been explored, scientific investigations must be continued in order to improve our understanding of geological, chemical and biological processes governing the formation, size and diversity of mineral deposits. Another aspect concerns impact studies. The definition of a biological reference condition, which aims to understand the impact of possible exploitation on deep-sea biological activity, constitutes an important stage in the arrival of industry in the deep sea. Active hydrothermal sites should not be considered as potential mining sites due to the temperature (400 °C) and acidity of fluids circulating at these sites. The development of methodologies to locate and assess inactive mature deposits (whose growth is now complete) is a challenge to be met.

In terms of metals, the European economy is largely dependent, often by over 90 %, on imports. Ocean mineral resources therefore represent interesting assets for Europe from a point of view of its raw materials supply. A single country will not be able to conduct all the necessary research. Europe will need to determine its geopolitical stance in relation to other major regions of the world and fund research in international waters, rather than restricting its efforts, as is currently the case, to its own economic waters. This is a major challenge if Europe is to retain its global leading position from a scientific and technological point of view and be in the running for the economic opportunities these resources represent.

Over the past few years, the mining industry has begun taking an interest in hydrothermal mineral deposits. Mining permits were granted in 2010 and 2011 for hydrothermal fields in the Red Sea and Papua New Guinea, located respectively at depths of 2,000 and 1,700 m. More recently, in July 2011, the ISA approved four new exploration applications in international waters. Two of these approvals were for nodules in the Pacific. The other two were granted, for the first time, for the exploration of hydrothermal sulphides in the Atlantic Ocean to Russia and in the Indian Ocean to China.

Chapter 5
Scientific Knowledge and Challenges Related to Hydrogen

Jean-Luc Charlou, Jean-Pierre Donval, Fabrice Brunet,
Manuel Munoz and Olivier Vidal

Hydrogen, the Energy of the Future?

Hydrogen is endowed with excellent physical and chemical properties, like its very high calorific value (three times higher than that of gasoline). With increasing gasoline and gas prices and diminishing fossil fuel reserves, hydrogen is emerging as a clean and renewable alternative energy source. The political and industrial worlds are beginning to see hydrogen as one of the fuels of the future. Several hydrogen production solutions exist, all based on artificial processes, which themselves require energy. Currently, 96 % of hydrogen is produced by thermochemical processes (48 % by natural gas reforming, 30 % by hydrocarbon reforming and 18 % by carbon gasification) and the remaining 4 % by water electrolysis. These processes require the use of fossil fuels (with CO_2 production); their cost therefore directly depends on oil prices.

Hydrogen is also naturally produced by certain bacteria in abiotic conditions during interactions between aqueous fluids and rocks. Campaigns conducted at sea by Ifremer over the past 20 years have shown that large quantities of hydrogen and hydrocarbons are emitted by smokers near the Mid-Atlantic Ridge. Good

---

J.-L. Charlou (✉) · J.-P. Donval
Métallogénie, Géosciences Marines, Centre Bretagne,
Ifremer, BP 70, 29280 Plouzané, France
e-mail: jean.luc.charlou@ifremer.fr

J.-P. Donval
e-mail: jean.pierre.donval@ifremer.fr

F. Brunet · M. Munoz · O. Vidal
Observatoire Terre-Univers-Environnement,
Université Joseph Fourier, BP 53, 38041 Grenoble Cedex 9, France
e-mail: fabrice.brunet@obs.ujf-grenoble.fr

M. Munoz
e-mail: manuel.munoz@obs.ujf-grenoble.fr

O. Vidal
e-mail: olivier.vidal@obs.ujf-grenoble.fr

Y. Fouquet, D. Lacroix (eds.), *Deep Marine Mineral Resources*,
DOI 10.1007/978-94-017-8563-1_5, © Éditions Quæ 2014

knowledge of the processes responsible for this natural hydrogen production and of the quantities produced is an essential starting point in the assessment of its economic potential. This involves field characterisation together with laboratory experimentation simulating natural conditions.

Research on Mid-Ocean Ridges

The initial objective of research is first and foremost to explore ridge segments. Exploration may lead to the discovery of sites which are then studied in detail to determine the geological context and the geochemistry of the fluids emitted.

The second objective is to understand the geochemical and thermodynamic processes resulting in hydrogen production. A third objective is to assess the hydrogen flow on the active site, to evaluate the resource's profitability and finally to study industrial recovery concepts and methods with a view to possible future exploitation.

Within the framework of mid-ocean ridge study programmes conducted by Ifremer over the past 15 years or so, seawater interaction with basalt rock and more specifically with the deepest mantle rock (peridotites) has revealed the existence of a high natural hydrogen flow from hydrothermal vents, associated with other hydrocarbon gases. This natural production is an inexhaustible and sustainable energy resource. This long-standing research, conducted mainly along the slow-spreading Mid-Atlantic Ridge through deep-sea exploration programmes, has resulted so far in the discovery of seven active hydrothermal sites producing large quantities of hydrogen (Fig. 5.1).

These results are the outcome of a series of research initiatives conducted successively first of all through the French-American Ridge Atlantic programme (FARA 1989–1996), then through European programmes MAST II-MARFLUX ATJ (1994–1997), MAST III-AMORES (1997–2000), as well as bilateral French-American and French-Russian cooperation. The many surface and subsurface exploration campaigns carried out over this period and until 2007 (Ridelente, Microsmoke, Faranaut, Diva, Flores, Iris, Serpentine, Momardream) revealed the serpentinization process known along slow-spreading ridges and confirmed the close link between the presence of mantle rock and the production of hydrogen and methane. Generally speaking, seawater-basalt interaction produces fluids which can have different geochemical signatures and are generally low in hydrogen. High H_2 concentrations can however be observed during eruptive events. Our work at the Rainbow site (36° 14′ N-MAR) and Logatchev (13° 45′ N-MAR), located along the Mid-Atlantic Ridge, shows a high and constant release of hydrogen from 1997 to 2007.

Recent work carried out on the ultraslow-spreading Arctic Ridge confirms the presence of mantle rock outcrops also associated with hydrogen and methane emissions. Seawater interaction with mantle rocks, at fracture zones, is therefore a phenomenon common to slow- and ultraslow-spreading ridges. This natural chemical process produces hydrogen (primary gas) in large quantities and inorganic hydrocarbons synthesised by catalysis (Fischer-Tropsch reactions) at high pressure and high temperature in subcritical or supercritical conditions.

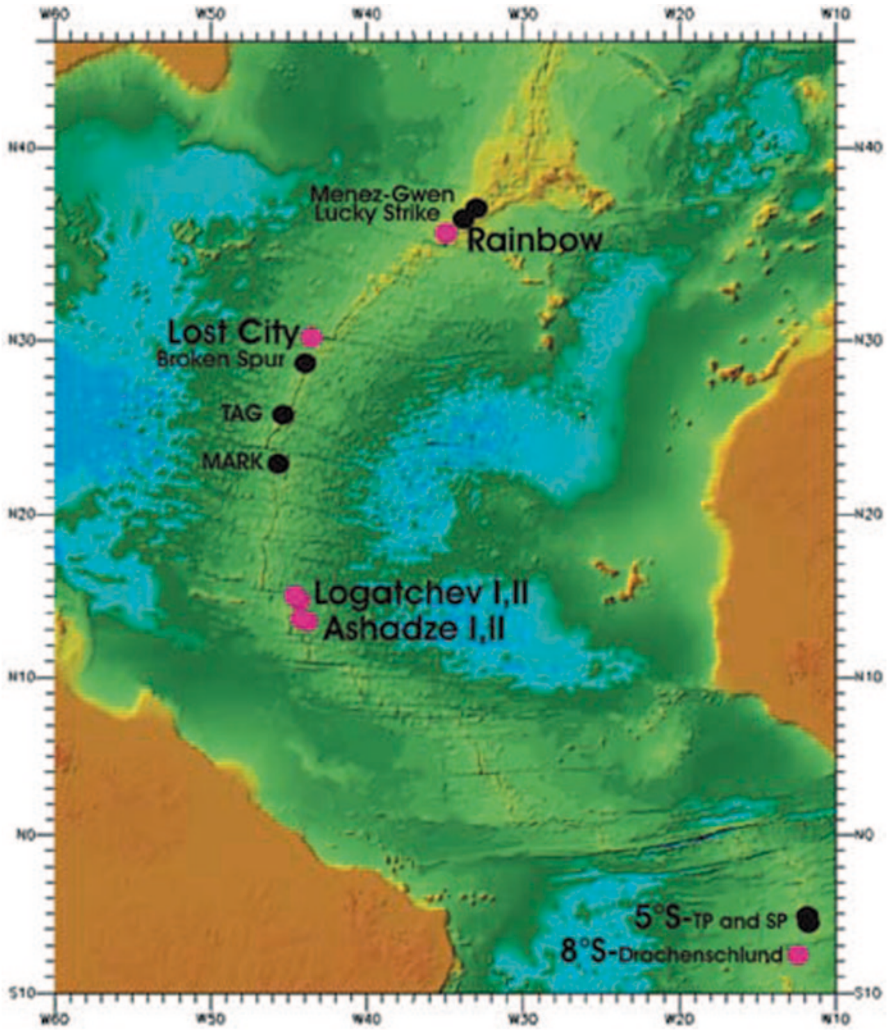


Fig. 5.1 Active high temperature sites discovered and explored to date on the Mid-Atlantic Ridge (*black* basalt sites; *pink* peridotite sites). (From Charlou et al. 2010)

This type of catalytic reaction is well known and has been long applied in the oil industry. Among the hydrocarbon compounds identified, other than volatile carbon gases, we also note the presence of heavier hydrocarbons and oxidised organic compounds (carboxylic acids). Another consequence of the high concentrations of hydrogen found in fluids is its impact on deep-sea bacterial flora, explaining the mixture of abiogenic and biogenic molecules synthesised during hydrothermal convection and found in fluids.

Since 1995, seven active high (>350 °C) or medium (~90 °C) temperature sites have been discovered in the mantle, all producing large quantities of hydrogen

Table 5.1 Hydrogen enrichment, observed on hydrothermal sites discovered in the Earth's mantle in the North Atlantic

Hydrothermal site	CO_2	CH_4	H_2	N_2
Lost city (30° N)	–	9.8	82.5	–
Rainbow (36° 14′N)	42.7	6.6	42.7	4.8
Logatchev I (14° 45′ N)	18.8	11.1	53.5	–
Logatchev II (14° 45′ N)	26.3	5.1	47.0	–
Ashadze I (12° 58′ N)	12.9	3.9	62.4	–
Ashadze II (12° 58′ N)	n.d.	2.3	76.5	–

(Table 5.1) and for which accurate flow calculations remain to be made. Diffuse low temperature fluids enriched in H_2 and CH_4 are emitted from many diapiric serpentized seamounts. These emissions occur at various depths (up to 4,100 m at Ashadze at 13° N). In all cases, the fluids have a relatively uniform composition, controlled by the phase separation process. They are derived from seawater interaction with mantle peridotites, as many serpentized rocks are found at the outcrop.

This table indicates the mole percentages of each gas (from Charlou et al. 2010).

What Laboratory Experimentation Tells Us

The physical and chemical conditions which lead to the formation of natural hydrogen in the ocean environment can be reproduced in the laboratory (Fig. 5.2). An experimental approach enables us to independently survey and quantify the effect of each of the important parameters (temperature, pressure, duration, chemistry of seawater, chemistry and mineralogy of solid reagents, mineral grain size, water-rock interaction, etc.) involved in the natural process. However, laboratory experiments have a time scale around 10,000 times shorter than that of the equivalent process in the natural environment. For this reason, experiments are generally carried out in optimal reaction conditions, for small-scale systems (finely ground solids, rock samples measuring only centimetres) and water quantities that are often higher than those available in the natural environment. Thanks to experimental work performed on interactions between peridotites and seawater between 200 and 450 °C and between 0.5 and 3 kilobars (1 kilobar = around 1,000 times atmospheric pressure), the complexity of natural chemical reactions resulting in hydrogen production has been greatly elucidated. The rate of these reactions (chemical kinetics) is well known for hydrogen formation, but remains relatively poorly defined for the production of hydrocarbon gases.

We know today that the primary ferromagnesian minerals that make up peridotites are destabilised in the presence of seawater at temperatures below 400 °C, to form magnesium hydrated minerals such as serpentine (Fig. 5.3a), simplified formula $Mg_3Si_2O_5(OH)_4$, and possibly talc, $Mg_3Si_4O_{10}(OH)_2$ or brucite, $Mg(OH)_2$, together with magnetite (Fe_3O_4) (Fig. 5.3b). While iron is present in primary minerals (before hydration) in ferrous form (Fe^{2+}), it is 1/3 ferrous and 2/3 ferric (Fe^{3+})

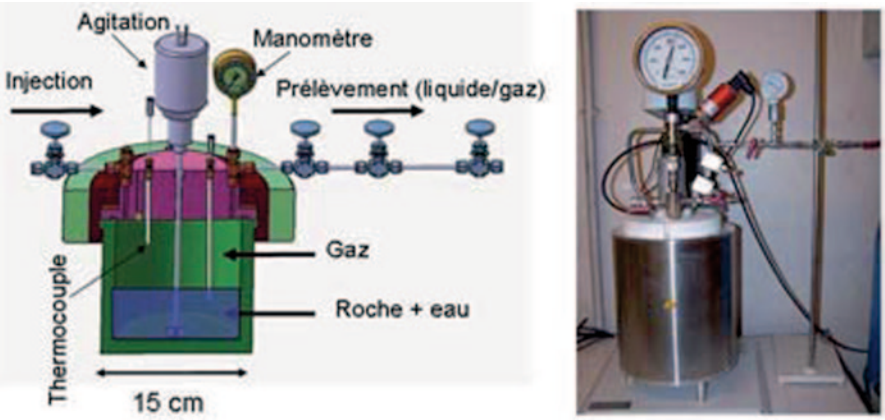


Fig. 5.2 Sampling autoclave used for hydrothermal alteration experiments. The fluid and gas can be sampled and analysed during the experiment, solids are characterised after the experiment

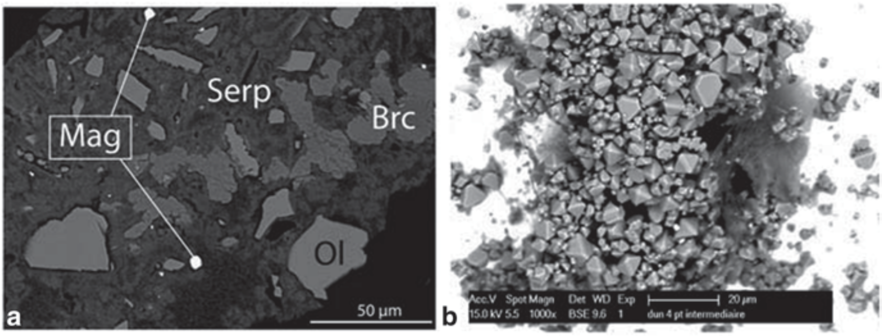


Fig. 5.3 Scanning Electron Microscopy images showing the experimental products of peridotite alteration. **a** Illustration of the reaction: olivine + water = serpentine + brucite + magnetite + H_2. **b** Clusters of magnetite crystals; H_2 production is intrinsically linked to the formation of magnetite and serpentine. *Serp* serpentine, *Brc* brucite, *Mag* magnetite

in the magnetics produced during hydration. Alongside the hydration of oceanic peridotites, progressive oxidation of the rock therefore occurs, made possible by the simultaneous reduction of seawater. In the laboratory, it is therefore possible to show that one mole of dihydrogen is formed per mole of magnetite produced according to the following redox reaction: $3Fe^{2+}O + H_2O \rightarrow Fe^{2+}(Fe^{3+})_2O_4 + H_2$.

Recent experimental and spectroscopic data obtained at the *Institut des sciences de la Terre* (ISTerre) and at Swiss Light Source (SLS) have fine-tuned this balance by showing that the formation of serpentines could itself produce hydrogen. Thanks to fine measurements of reactions' progress by X-ray absorption spectroscopy, as well as magnetic methods through collaboration between ISTerre and the *Laboratoire de géologie de l'écolenormalesupérieure* (Paris), we now know that it

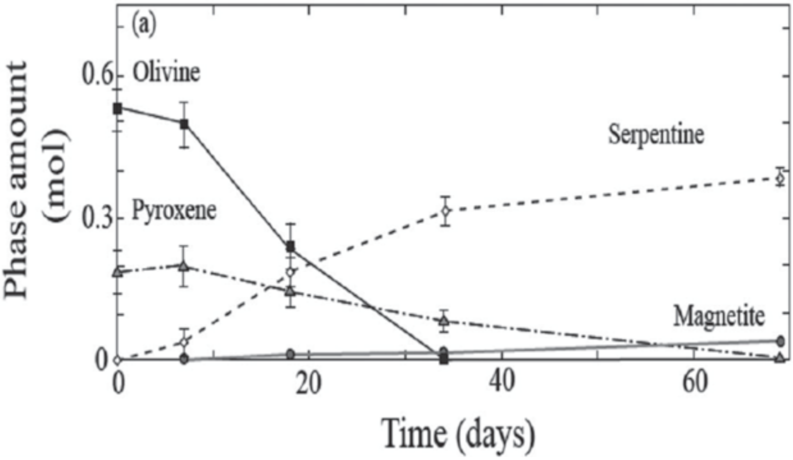
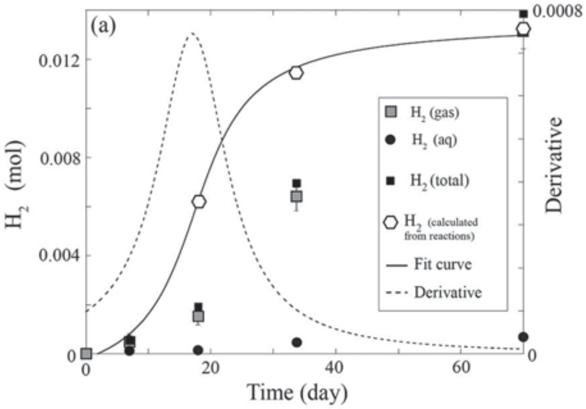


Fig. 5.4 Evolution over 70 days of the relative proportions of primary minerals of a peridotite (olivine, pyroxenes) and the products of its alteration in the presence of water (serpentine, magnetite) at 300 °C and 300 bars. (From Marcaillou et al. 2011)

Fig. 5.5 Measurement of hydrogen produced during the transformation of a peridotite in the presence of water at 300 °C, 300 bars, over 70 days. (From Marcaillou et al. 2011)



is mainly the dissolution rate of olivine $(Mg, Fe)_2SiO_4$ that controls the hydrogen production rate from peridotite hydration (Figs. 5.4 and 5.5). By coupling laboratory data and thermodynamic models, it is now possible to extrapolate experimental results to natural conditions and simulate the composition of dissolved species (cationic and H_2 gas) in a given volume of seawater which balances, under pressure and temperature, with an ocean peridotite.

Reaction mechanisms which lead to the formation of hydrocarbon gases have also undergone a number of experimental studies, but the results are very contrasting both in terms of outputs and kinetics. Experimental work converges towards a possible reduction in CO_2 dissolved in seawater in favour of methane or other hydrocarbon gases according to Fischer-Tropsch processes. These reactions and hydrocarbon polymerisation could be catalysed by the surface of metals (Fe-Ni alloy) or oxides (magnetite) present in hydrated oceanic peridotites. However, the very low outputs (less than 0.04 % dissolved CO_2 transformed into methane), dependence on the catalyst concentration, possible contamination and catalysis of the experimental reactor by the metal are some of the parameters that are difficult to control, therefore limiting the application of experimental data in the natural environment. This opens up a vast area for experimental and analytical research.

Quantities of Natural Hydrogen

Due to the dilution and gradual breakdown of hydrogen released into the deep sea, flux calculations and estimations of hydrogen and other hydrocarbon gases are difficult to make. However, we know that the hydrogen concentration extracted from a hydrothermal vent in the mantle is around 10–16 mM/kg. A hydrothermal vent around 40 cm in diameter releasing fluid at a rate of 1 m/s injects around 1 million m^3 of hydrogen a year into the water mass. By including all active, high temperature vents within a site, and by taking into account all the related warm diffusion areas, the hydrogen flux from serpentinization along the slow-spreading Mid-Atlantic Ridge can be estimated at around 10^{11} mol/year, with a range of estimations: 190×10^9 mol/year (Keir 2010), 167×10^9 mol/year (Cannat et al. 2010), 89×10^9 mol/year (Charlou et al. 2010).

The CH flux is estimated at around 84×10^9 mol/year by Emmanuel and Ague (2007), 20×10^9 mol/year by Keir (2010), 25×10^9 mol/year by Cannat et al. (2010) and 8×10^9 mol/year by Charlou et al. 2010.

However gas fluxes (H_2, CH_4) from oceanic serpentinization remain poorly known. The available data require confirmation by future studies. Nevertheless, it is certain than slow-spreading ridges are a natural hydrogen source, indeed that is not yet fully understood, but that represents a potential energy source that should be considered in the Earth's global energy balance.

Future Research Strategies

Currently, seven active sites producing large quantities of hydrogen have been discovered along the Mid-Atlantic Ridge between 8° S and Azores Triple Junction. Our work shows that slow-spreading ridges have alternative natural hydrogen sources to those derived from the burial and maturation of organic matter in sediment basins, yet here this source is not mastered. What quantities of hydrogen and hydrocarbon gases are abiotically generated from the mineral ore? Estimations remain to be made and can only be specified by continued exploration of slow-spreading ridges and greater knowledge of the deep sea. Yet high hydrogen concentrations measured in fluids on the seven active sites (Rainbow, Lost City, Ashadze 1 and 2, Logatchev

1 and 2, site 8° S) currently known along the Mid-Atlantic Ridge and preliminary calculations performed show that this gas flux is gigantic.

These questions are on the agenda and currently under debate within the international scientific community. Hard and fast answers can only be provided by continuing to explore the deep sea, and in particular slow- and ultraslow-spreading ridges, through the collection of field data and by seeking new sites, based on two guiding principles: a scientific multidisciplinary approach and a long term vision.

To estimate the quantity of hydrogen that could be exploited, the natural production-migration process will also need to be understood and modelled on a large scale. As outlined above, it is now established, mainly based on experimental simulations, that hydration of the oceanic crust generates hydrogen and, to a lesser extent, methane, by rock hydration (peridotites). However, hydrogen production does not only depend on mineral hydration reactions, as studied in the laboratory, but also on seawater availability and transport (fluid circulation in rock) in the fracture area. Diffusive and advective seawater transport in the rock is not independent of hydration reactions, as these reactions involve major variations in volume (and fracturation) and also produce heat (highly exothermic reactions). Different couplings occur (fluid chemistry, crystal chemistry, petro-physics) whose complexity can only be addressed by numerical modelling and appropriate changes in scale (scale of the mineral, the fracture, large active faults, convection cell, etc.).

Similarly, we know that dihydrogen has high mobility and a high diffusive capacity, which limits its storage possibilities in the natural environment. Yet does this imply that dihydrogen has a very short residence time in the rocks in which it is produced? Does it migrate, carried by fluid circulation, in the form of dissolved gas, or could dihydrogen be trapped locally in the form of gas pockets? Ultimately, how can dihydrogen reserves be estimated based on degassing balances? Are these reserves sufficient to consider, in the longer term, the recovery of these gases from high temperature vents ($>350\,°C$) located at depths ranging from 2,000 to 4,000 m?

In quite an unexpected way, the relatively high serpentinization rates shown through experimental work could allow industrial land-based hydrogen production processes to be considered, using feedstocks containing Fe^{2+} that are able to react in the presence of water to form ferric phases (industrial geoinspired process). Like natural processes, iron oxidation is accompanied by water reduction and dihydrogen production.

This example of natural dihydrogen clearly illustrates how fundamental research geared towards the understanding of a natural phenomenon can ultimately lead to the identification of new avenues towards applied research, with possible industrial development prospects.

Chapter 6
International Law and Its Evolution

Élie Jarmache

Framework

Access to marine mineral resources for exploration and exploitation purposes is not unrestricted. It is tightly controlled both by the international law of the sea and by national legal systems. The international law of the sea, long before its most recent version (that of the 1982 United Nations Convention), established the legal foundations of the new regime of resources in a resolution of the United Nations General Assembly on 17th December 1970 (resolution 2749), formulating the "*principles governing the sea-bed and the ocean floor, and the subsoil thereof, beyond the limits of national jurisdiction*". The principles can be summarised through two complementary ideas which are incorporated in the Convention: firstly, national non-appropriation of seabed resources, and secondly the affirmation that these resources are for the benefit of mankind, established as a new subject of the law, and are the common heritage of mankind.

As if in echo, a few years later, as the Third Conference on the Law of the Sea was setting to work (1973), the United Nations General Assembly confirmed the principle of permanent sovereignty of a State over its natural resources. This principle, which applies to all natural resources, also applies to marine resources within the limits of national jurisdiction. It was formally laid down in the Charter of Economic Rights and Duties of States adopted in 1974, as the new global economic order was becoming established.

The combination of this principle of permanent sovereignty of States and the advent of common heritage of mankind fully reflect the fact that access to marine mineral resources is not unrestricted. Their exploration and exploitation are controlled activities.

É. Jarmache (✉)
Secrétariat général de la mer, 69, rue de Varenne,
75007 Paris, France
e-mail: elie.jarmache@pm.gouv.fr

Y. Fouquet, D. Lacroix (eds.), *Deep Marine Mineral Resources*,
DOI 10.1007/978-94-017-8563-1_6,

The world has changed since this time. Various major political, economic and scientific shifts have altered many balances, but this principle has remained invariant.

This is why Part XII of the Convention on the Law of the Sea, on the "*protection and preservation of the marine environment*", after having indicated in its introductory article (article 192) that States have the obligation to protect and preserve the marine environment, is quick to reaffirm in the following article the sovereign right of States to exploit their natural resources (article 193). The relationship that is to exist for many years to come thus appears between the sovereign right to exploit resources and the obligation to protect the marine environment, with a varying intensity between the two terms of this relationship from one period to another.

As if to prolong this situation, the Convention on Biological Diversity, adopted in Rio in 1992, confirms the maintenance and ongoing relevance of this relationship between sovereign right and environmental concern. In its article 3, entitled "Principle", it is stated that "*States have, in accordance with the Charter of the United Nations and the principles of international law, the sovereign right to exploit their own resources*".

Seabed and ocean floor resources within and beyond the limits of national jurisdiction are therefore not unrestricted. This is a major legal and political criterion in a world that is thus undergoing a paradigm shift.

The Seabed Beyond National Jurisdiction

The granting of a legal status that exempts the seabed from the regime of the high seas is an innovation that can be qualified as "revolutionary" in the law of the sea. The 1982 United Nations Convention makes a distinct, clear-cut separation between the water column and the seabed (and subsoil), that was not made by the 1958 Geneva Convention which only addressed the high seas and encompassed both elements in the regime of freedom of the high seas.

As a reminder, the definition of the high seas in the UNCLOS Convention makes no reference to the seabed beyond national jurisdiction. The high seas, in this definition, are composed of all parts of the sea that are not included in the EEZ, in the territorial sea or in the internal waters of a State. This is a clear indication that the distinction between the water column and the seabed is no longer made beyond the limits of national jurisdiction. Freedom remains to be the rule, such as a freedom of navigation and overflight, as well as with greater relativity, freedom of marine scientific research, fishing, cable- and pipeline-laying.

From the very first article of the UNCLOS Convention, a specific marine Area is defined. The Area is composed of the seabed and ocean floor and subsoil thereof beyond the limits of national jurisdiction; this clearly marks the desire for it to be exempt from all sovereign rights of States. In reading the Convention, an obsession with this principle laid down in article 137, paragraph 1 appears to emerge:

"*No State shall claim or exercise sovereignty or sovereign rights over any part of the Area or its resources, nor shall any State or natural or juridical person appropriate any part thereof. No such claim or exercise of sovereignty or sovereign rights nor such appropriation shall be recognized.*"

The same article, at paragraph 3, clarifies the legal regime, which extends beyond resources alone, as it states that: "*No State or natural or juridical person shall claim, acquire or exercise rights with respect to the minerals recovered from the Area except in accordance with this Part. Otherwise, no such claim, acquisition or exercise of such rights shall be recognized.*"

The Convention therefore makes a two-fold exemption for the Area: in relation to national jurisdiction and in relation to the high seas. This exemption results in the creation of a legal regime subjecting access to mineral resources to a more elaborate authorisation regime combined with assured control.

The appearance of the Area within the typology of marine zones is an indicator of the changes which will lastingly affect the perception that States and operators have of access to natural seabed resources.

Part XI of the Convention, completed by an agreement relating to its implementation which entered into force in 1994 (intended to facilitate the United States' adhesion which was believed to be imminent), introduces a legal regime whose details may have frightened off certain countries tempted by the possibility of deep-sea mining, but not at the expense of the establishment of a supervisory authority considered an excessively bureaucratic and pernickety measure. This is the unique reason for the United States' vote against the adoption of the 1982 Convention and the US has still not ratified this text.

Where European countries abstained and were heavily criticised (Germany, for instance), France was very quick to declare that it was in favour of the Convention, given its significant, long-standing investment in research with the ultimate goal of marine mining activities. Ifremer was registered as a pioneer investor and, thanks to this title, was granted the protection of investments already made for polymetallic nodules. It should be noted that this also stretched beyond financial protection, as the conditions of negotiations resulted in the choice of an area considered to be of great interest.

The Area and activities conducted therein are governed by a newly formed international organisation for the management of this zone and its resources, established by the Convention. The International Seabed Authority, or ISA, which has its headquarters in Kingston, Jamaica, is a truly international organisation with a legal personality and all the attributes of such an organisation: a Secretariat, an Assembly and a Council. All States party to the Convention are members of the ISA: to date, 162 States, including France since its ratification in 1996 as well as the States of the European Union, the EU itself, having joined the Convention, are members of the ISA.

The Assembly is qualified as the authority's "supreme organ", but it is the Council of 36 members that constitutes the authority's "executive organ" (i.e. decision-making body); the role of the Assembly is rather to ratify the council's decisions.

The importance of the Council's role becomes apparent when we discover that it is expressly attributed by article 163 of the Convention with two subsidiary organs: an Economic Planning Commission and a Legal and Technical Commission.

The first did not survive the reorganisation generated by the 1994 agreement which, in a single sweep, also suspended the existence of what should constitute the ISA's commercial arm, the Enterprise, designed as an international mining operator, in competition with operators under general jurisdiction. The competences of the Economic Planning Commission are exercised by the Legal and Technical Commission. The attributions of the Enterprise were transferred to the Secretariat.

It is interesting to note that the 1994 agreement created a Finance Committee in charge of examining financial issues relating to activities to be conducted in the Area (contractor relations, their financial obligations), to advise the ISA's organs on budgetary aspects. The idea of a body in charge of finance is indicated in the Convention, among the Council's roles and responsibilities, but without any details on the urgency of its creation. The 1994 agreement overcomes this hurdle by going beyond the letter of Part XI, as it makes this body into an operational committee with a fairly detailed and explicit mandate, including the examination of the ISA's provisional budget.

The role of the Legal and Technical Commission should be highlighted when it comes to questions concerning access to mineral resources. The commission is made up of a minimum of 15 and a maximum of 25 experts, elected for a period of 5 years, and aims to take account of all geopolitical sensitivities and to include all possible aspects of the scientific, technical, legal and environmental skills required to evaluate seabed applications. The experts, who are put forward by the State, are considered to be independent from the moment they are elected, in order to prevent conflicts of interest.

This commission is, to a certain extent, in charge of controlling contractors (enforcement of obligations, opinion on annual reports…). It has a normative role as it is in charge of drawing up the most important texts, i.e. the regulations for exploration or exploitation of mineral resources. It established the two sets of regulations for the exploration of nodules (2000) and sulphide deposits (2010). The regulations on cobalt-rich crusts are currently in progress.

Article 165 of the Convention is entirely devoted to outlining the functions of this commission, however here we shall simply cite the first of these functions, which introduces the list of skills. The commission shall "*make recommendations with regard to the exercise of the Authority's functions upon the request of the Council*". There is potential for development behind the notion of "the Authority's functions". The central role of the duo formed by the Council and the Legal and Technical Commission could not be clearer.

The Council is made up of 36 members, and its composition in terms of the origin of certain members breaks with the classic rules of the law of international organisations, with the representation of:

- States considered to be the greatest consumers or importers of the commodities produced from the categories of minerals to be derived from the Area (four States to be elected).

- States among the greatest investors for the preparation and implementation of activities in the Area (four States out of eight to be elected). Here clarification is necessary for France, which is a member of the Council based on this provision of the Convention. This is the direct effect of the extent of French investments many years before the Authority was established. There is also the will of certain investor States, which joined in later, to modify this classification and we cannot rule out the possibility that one day, with French investments (in particular public investments) lagging, France may no longer be on the Council as part of this “investment-based college”.
- States considered among the main mineral exporters for their national jurisdiction and for minerals extracted from the Area (four States to be elected, including two developing States).
- Developing States representing special interests (six States to be elected from among States with large populations, States which are land-locked or geographically disadvantaged and least developed States).
- Finally, half of the Council, i.e. 18 members, elected according to the more classic principle of ensuring an equitable geographical distribution, based on geographical regions (Africa, Asia, Eastern Europe, Latin America, Western Europe and other States including non-European Western States). Each geographical region shall have at least one representative.

The Council members are elected for a 4-year period.

This analysis of the Council’s composition fairly clearly indicates why it is the executive organ of the authority, gathering economic interests through the qualification of its members, and political expression by applying the usual legal rules in force in the system of international organisations. Here again, to cite an example of the Council’s pre-eminence, in the event of disagreement of the Assembly on a Council recommendation, the Assembly cannot make the decision and must refer it back to the Council for re-examination in light of its views. Nothing is said on the right to the “last word” and, given the Council’s composition, it is not difficult to see that this lies within its bounds, even if the legal and diplomatic arrangement remains to be established.

Towards an International Mining Code

Two sets of regulations have been adopted over the past decade: in 2000, Regulations on Prospecting and Exploration for Polymetallic Nodules in the Area and in 2010 Regulations on Prospecting and Exploration for Polymetallic Sulphides in the Area. Without entering into the details of each of these sets of regulations, it is worth highlighting the elements common to both of them, where they express the same fundamental data on the common heritage of mankind developed into a pragmatic mining law.

The two sets of regulations involve an application presented in two parts of estimated equal value of the area to be explored; one part must allow a sector to be set up for exploitation by the Enterprise once it is able to conduct commercial mining operations, while the other part shall be allocated to the applicant. The choice between the two parts is in principle not the applicant's prerogative but rather that of the ISA, upon the advice of the Legal and Technical Commission.

The legal means by which it is recognised and allocated to an operator is that of a 15-year contract, which is divided into 5-year intervals with reports on the activities conducted and the expenditure incurred, in order to prove that the operator is serious and is following his work schedule as submitted at the time of his application. While both sets of regulations include the imposition of a fee, they differ in the terms and conditions relating to its payment. In the case of sulphides, this is either a fixed fee of US $ 500,000 paid once, or a fixed fee of US $ 50,000 dollars plus, when the time comes, an annual fee calculated based on a revenue-sharing provision for the Enterprise as a joint-venture partner. The terms of this financial arrangement for nodules are different for reasons relating to negotiations prior to the entry into force of the Convention.

On the basis of these two sets of regulations, an international mining law is established, liable to lead to a full-fledged mining code, which will gradually gather legal elements on protection of the marine environment related to mining activities in the Area. This provides a highly interesting normative perspective in terms of the evolutions affecting stakeholders (States, mining companies, their transnational character, NGOs). The question of the responsibility of States sponsoring an application by a mining company appears to have been sufficiently important for the ISA to have requested an advisory opinion from the Seabed Disputes Chamber of the International Tribunal for the Law of the Sea in Hamburg.

Requested in 2010, the opinion was issued on 1st February 2011 and concluded that a sponsoring State has responsibilities from which it could not easily be exempt, the main reasons being based on due diligence to control the activities of the entity it is sponsoring. This widely applies to protection of the marine environment, but also to all the obligations incumbent upon the operator. It is true that by its very nature, the sponsoring State's obligation is one of conduct, but the Chamber was careful to note that "*the standard of due diligence may vary over time and depends on the level of risk and on the activities involved*".

There is no certainty that the sponsoring State shall be exempt from responsibility by simply proving its efforts. Similarly, the level of control of due diligence will depend on concrete situations, and this will begin by checking that the national legal system includes laws or regulations to implement control of the operator. This should be an objective right and not simply a contractual arrangement between the State and the sponsored entity. It is clear that the combination of regulations, Council decisions, recommendations and observations by the Legal and Technical Commission, together with the advisory opinion issued by the Chamber of the Tribunal, shows the constitution of a concrete legal corpus which can only expand.

In this respect, the ISA's competences in terms of scientific research and protection of flora and fauna will act as a driver to ensure greater efficacy of its mandate in the Area. The continuous development of its scientific workshops associating experts from its Legal and Technical Commission with experts from academic circles (mainly American universities) will provide a frame of reference for many international conferences addressing the seabed from a point of view of its protection, such as the creation of marine protected areas in the high seas and the Area. Collaboration is being set up with regional institutions such as OSPAR (The Convention for the Protection of the marine Environment of the North-East Atlantic).

A consolidation phase of the ISA can therefore be predicted, with much support, of all natures, from among developing and developed States and among NGOs seeking to make of it a tool for the governance for which they are calling.

Chapter 7
Training Organisations and Establishments in France and Europe

Alain Cheilletz and Marcia Maia

Demand for Raw Materials

The recent rise in the cost of energy and mineral raw materials, together with the European Union's high dependence on raw material imports, has raised awareness of this major weakness for the development of modern societies among the main political and economic players. This observation is coupled today with relevant strategic questions at a time when the Western energy systems industry, dominated by carbon, is evolving towards propulsion and energy production systems that require increasing quantities of metals; this further accentuates international dependence. The entire periodic table of elements is concerned, but the greatest challenges will doubtlessly lie within the field of high technology metals (also referred to as "small metals").

The European Commission's Raw Materials Initiative (COM [2008] 699) is entitled "Meeting our critical needs for growth and jobs in Europe". The ProMine Project launched in the wake of this initiative is designed to meet the needs in terms of basic knowledge on geological potential, metal deposits and their exploration in Europe, as well as the development of more efficient extraction technologies compatible with the maintenance of a sustainable environment.

Major surface or deep-sea exploration campaigns are in progress in Scandinavia (base metals, gold, uranium), Poland (base metals and small metals) and the Iberian Peninsula (base metals, precious metals).

In France, while awaiting a hypothetical resumption of mining exploration (base metals, precious metals, uranium and coal in particular are targeted) that should be

---

A. Cheilletz (✉)
École nationale supérieure de géologie deNancy,
rue du Doyen Marcel Roubault, 54500 Vandœuvre-lès-Nancy, France
e-mail: alain.cheilletz@crpg.cnrs-nancy.fr

M. Maia
Institut universitaire européen de la mer (IUEM),
Université de Bretagne occidentale, Place Nicolas Copernic,
29280 Plouzané, France
e-mail: marcia@univ-brest.fr

Y. Fouquet, D. Lacroix (eds.), *Deep Marine Mineral Resources*,
DOI 10.1007/978-94-017-8563-1_7, © Éditions Quæ 2014

encouraged by the wealth of our subsoil (around ten exploration licenses are currently being examined), the main players' efforts currently focus on the EEZ and the submarine area, which constitutes for France a potential source of mineral raw materials.

Alongside this targeted effort, the deployment of a controlled raw material supply policy draws first and foremost upon government initiatives aimed at better price regulation on international markets, in order to avoid speculative effects related to sharp price variations as far as possible. This is the intent of the policy currently implemented by France within the G20. In the field, as concerns the research and development aspects of this policy, mobilisation involves reactivating the links between the various players: universities, public scientific and technical research establishments (CNRS-Research Institute for Development, IRD), public industrial and commercial establishments (BRGM, Ifremer, National Agency for Radioactive Waste Management, IFP, Atomic Energy Commission) and major industrial partners (Total, GDF-Suez, EDF, Areva, Eramet, Rhodia, Eurogia, Schlumberger).

The role of several French SMEs and investment funds that are currently very active in this field should not be overlooked either. The newly created programmatic group 2 of the ANCRE Alliance identifies three key challenges in terms of fossil and geothermal energies (V8/08-06-2010). The first is to boost energy independence by re-examining the potential of fossil and geothermal resources on a national scale (including French overseas territories); the second is to meet the urgent need to respond to climate change; the third is to identify and increase the critical metal resources used in new carbon-free energy sectors.

As for CNRS, the majority of their Earth science research capacities are gathered within one of its ten institutes, INSU.

Among the various joint research units (UMR) and Earth science and astronomy observatories (OSU) which make up INSU, several are specialised in oceanographic sciences, in particular marine geosciences. Among these entities, the OSU IUEM (the European University Institute of the Sea) in Brest is entirely devoted to research and training in marine sciences. This OSU is based on a close partnership between UBO, CNRS, IRD and Ifremer laboratories, as well as on strong links with the Brittany Maritime Cluster. LabexMer ("Laboratory of excellence" in marine research) boosts the visibility of this national marine cluster. Other national and international research groups exist in Villefranche-sur-Mer (GéoAzur, with support from the universities of Paris VI and Nice, CNRS and IRD) and at the Institute of Earth Physics of Paris (IPGP, marine geosciences). These teams show strong research and training potential in the field of marine geosciences in France.

In terms of research on natural resources, a major organisation effort was undertaken following the INSU foresight study in 2008. The establishment of a thematic committee on "Geological resources and sustainable development" was the pivotal element. Several actions followed, in particular the organisation of specialised foresight workshops (underground hydrogeological resources, basins), the creation of CNRS schools on resources (Nancy in 2010 then Orléans in 2011) and support for coordinated actions, within the framework of incentive actions as part of the CESSUR-INSU programme. Other parallel initiatives have been developed by CNRS, such as the GUTEC-PACEN programme (geology of uranium and thorium, extraction, conversion—programme on the downstream aspects of the cycle and nuclear energy), which aims to support research and development on the exploration of uranium and thorium deposits. As part of the deep-sea mineral resources foresight study, an evaluation was carried out of the potential of French laboratories in the field of knowledge and exploitation of submarine natural hydrogen resources. It is also worth noting the active collaboration between the National Agency for Radioactive Waste Management, CNRS and universities on underground storage of radioactive waste through the Forpro programme (deep geological formations).

Finally, the attribution of "*LabexRessources 21*" (laboratory of excellence on strategic metal resources for the twenty-first century) to research teams in Nancy grants this cluster recognition in the field of raw materials; it clearly demonstrates the government's will to organise French efforts on this theme.

Research Needs

In the conclusions of the report of the European Commission's Raw Materials Initiative, point 8 highlights the need to "*Promote skills and focussed research on innovative exploration and extraction technologies, recycling, materials substitution and resource efficiency*". As concerns CNRS-INSU (INSU Earth sciences foresight study 2011), the "Metallogeny of mineral resources" aspect appears as one of the key aspects structuring the French scientific community involved in issues relating to raw materials, alongside the aspects of "sediment basins" and "ground water hydrology". As for ore deposits, they constitute a specific case of land-based endogenous and exogenous transfer processes. The scientific challenges relating to these deposits are therefore shared with research in the fields of geodynamics and transfer/interactions between the asthenosphere, lithosphere and hydrosphere, and naturally involve a large share of the scientific community devoted to Earth sciences.

Today, the improvement in provisional metallogenic models relies upon:

- Determination of temporal and structural relations between deposits with geodynamics and paleostructures,
- Characterisation of the various phases of deposits,
- Geochronology and dating of mineral deposits (in particular U-Pb, Ar-Ar, Re-Os),
- Mineralogy (identification of new species, in particular in the field of small metals), petrography and experimentation, in particular resulting in thermodynamic data,
- Geochemistry with the tracing of the sources of metals, binders and fluids,
- Geophysical characterisation of deposits,
- Modelling: on the one hand, numerical and thermodynamic modelling of fluids transporting and depositing metals; on the other hand, three-dimensional and stochastic modelling of the subsoil (in particular modelling of uncertainties).

Even if all these objectives do not fully apply to the field of marine mineral resources, any significant progress in these metallogeny research areas should find an application in understanding submarine metal deposit formation processes. In terms of marine mineral resources, in particular hydrothermal sulphide sites, one of the research challenges is to improve understanding of the genesis of these deposits in relation to fluid circulation, plate tectonics and volcanism, as well as the nature of the substratum. This implies improving knowledge of ocean floors and seabeds on different scales and developing geophysical methods to obtain high resolution subsurface images, such as electrical imaging and mobile submarine gravity gradiometry using an autonomous underwater vehicle (AUV).

Earth Science Studies in France

In addition to the organisation of Earth science research efforts, the training capacities in this field in France must also be reviewed. Consideration of training is one of the recommendations of the European Commission, as well as of the mission statement of the French Ministry of Higher Education and Research. The prospect of a major increase in the demand for professionals in the field of geosciences has emerged "*as a consequence both of increased, lasting demand in the field of mineral and energy raw materials, and policies related to climate change*." (V. Pécresse, 30th October 2008, quoted by J. Varet 2009).

Training Geologists: Specialised Courses

Geologists are, through their training, an exception in the field of scientific studies. They are at the crossroads of two opposing types of reasoning, one being Cartesian, drawing upon theoretical reasoning to deduce laws that apply to different scientific and technical fields, and the other naturalist, drawing upon observation and analysis of the infinite complexity of the mineral and living world to attempt to understand its organisation. This results in a strong adaptive capacity to the complexity of the mineral world in general, and a desire to take a qualitative approach in addition to a quantitative approach, as solutions to problems posed are always evolving with time and the acquisition of new investigation methodologies. The teaching of this type of inductive reasoning characterises Earth science studies and doubtlessly constitutes their main attraction for young generations at these times of generalised defiance towards scientific studies, especially in the field of physics.

Courses in France and Worldwide

Far from shadowing the evolution of the job market in the field of mineral raw materials from 1980 to 2007 (a period which represented the low point of the economic cycle for this sector of activity), university courses in France kept their geologist training capacities practically operational. This aspect, which differentiates us from many countries, in Europe in particular (Great Britain for instance, despite its strong industry in this field and the global scope of activity composed by the countries of the Commonwealth), is no doubt due to the national and public nature of our university system, providing it with stability over time. We shall therefore refrain from jumping to all hasty conclusions in this field, reproducing situations which specifically concern Anglo-Saxon countries (Australia, United States, Great Britain, Canada), which are today confronted with a real shortage of technical executives in the field of geosciences and are currently largely calling upon a trained workforce from Europe in particular (France and Germany among others).

Courses: A Review

Geoscience courses are on offer in almost all university establishments in France (including French overseas territories) and for all levels of qualifications.

BTS Nancy and IUT

The *Brevet de techniciensupérieur* (higher technical diploma, BTS) in applied geology is offered at ENSG (see below) and LycéeLoritz in Nancy. It is a 2-year course and includes an 8-week work placement.

Several technological university institutes or IUTs specialised in civil engineering, geomechanics, resources and the environment offer a range of vocational training courses, in addition to the 2-year diploma courses in geosciences. These courses are offered across France and are today linked to universities.

Degree and Masters Courses

Today, France has a very wide range of geoscience courses. They are spread across 35 universities and 48 Masters courses. The specialisations taught cover the whole spectrum of geosciences, whether in the field of knowledge of the Earth system or the technological applications and mineral, energy and environmental resources associated with it.

Specialised Marine Geoscience Courses

In marine geosciences, the number of specialised courses is relatively low.

SML Masters Course (Sciences of the Sea and Shore), UBO-IUEM, Brest

The SML Masters course is the only one in France whose name indicates its specific marine focus and offers various specialisations covering a wide spectrum of marine sciences, from physics to law and economics. The marine geoscience specialisation offers three options covering aspects of geodynamics, geophysics and plate tectonics, sedimentology and petrology/geochemistry. This course enables students to specialise in data acquisition methods and techniques at sea through field missions on board vessels, and to learn about different geodynamic features, from ridges to margins, as well as the shore. The "physics and mechanics of continuous environments" specialisation offers students with a physics degree or engineering school qualification, as part of the marine geophysics option, a course in Earth sciences geared towards geophysics. The core module on challenges and issues enables students taking the different options to come together for a multidisciplinary module.

GéoAzur, Villefranche-sur-Mer

This marine geoscience research laboratory contributes to training through three teaching modules, one at Master 1 level and two at Master 2 level. They cover marine seismic activity and the comparative study of marine and terrestrial features, in collaboration with the Masters courses at the universities of Paris VI and Nice. The expedition on board the oceanographic vessel *Téthys*, dedicated to marine seismic activity and core sampling, is an asset in the training offered by this laboratory.

IPG Paris

As part of the Masters course in geosciences offered by IPGP (Institute of Earth Physics of Paris), several options address marine geosciences.

Engineering Schools

One Higher National School of Geology (ENSG-INPL, engineering school associated with the *Ecoles des mines* group), several higher engineering schools from the *Écoles des mines* group, the School and Observatory of Earth Sciences (EOST in Strasbourg) and LaSalle-Beauvais Polytechnic Institute complete the Masters level training offer.

ENSG Nancy The Higher National School of Geology in Nancy is the only French "*grandeécole*" in its field, i.e. that of geosciences, in particular in the fields of application of interaction between human activities and the geosphere. ENSG is today developing in four priority areas both in terms of teaching and research: mineral and energy raw materials; water; geotechnics, civil engineering, use of land and subsoil; and finally, the environment and safety, quantitative geology.

Since its beginnings (1948), ENSG has training around 3,500 graduates. Current year groups are of around 115 students (2010).

The Écoles des mines Group

The *École des mines* engineering school in Nancy offers one of the greatest research potentials among the French "*grandesécoles*". It comprises six research laboratories (in association with CNRS, INRIA (National IT and Automatic Control Research Institute) and INERIS (National Institute for Industrial Environment and Risks)) and two research teams, representing over 350 people. In the field of Earth sciences, ENS Mines-Nancy is a partner of three laboratories: LAEGO (environment, geomechanics and structures laboratory), INERIS, which has developed skills in monitoring structure stability, and the Laboratory of Geology and Mineral and Energy Resource Management in partnership with Henri Poincaré University in Nancy. The school also offers a geoengineering option as part of the civil engineering course.

Mines Paris-Tech offers as part of its civil engineering course a third-year option entitled "soil and subsoil", which focuses on the contribution of the subsoil to the functioning and development of society. The thesis traditionally constitutes a research and development assignment.

The *École des mines d'Alès* is divided between three sites, Alès, Nîmes (Gard) and Pau (Pyrénées-Atlantiques). It has a research centre devoted to the industrial environment and natural risks (LGEI), geared towards the sectors of waste recycling, energy and water industries.

LaSalle-Beauvais LaSalle-Beauvais Polytechnic Institute offers a 5-year higher education engineering course in geology, with specialities in geology, geotechnics and mining.

There is a marine geoscience speciality in the final year with a placement in Villefranche-sur-Mer or Brest at IUEM.

Specialised Higher Education Courses

CESMAT, the centre for advanced studies of raw materials, is an advanced training institution for senior executives in the field of mining. Since 1975, it has been offering seven high level courses, each for ten to twelve engineers and geologists all having already acquired professional experience. This has led to the establishment of a network of 2,500 trainees from around a 100 countries, with which the centre maintains ongoing relations. Through a permanent task team for the training of executives in the mining industry, the teaching can be adapted as needs evolve. CESMAT is tasked with a long term mission of establishing a network of relations with raw material producer countries by the French Ministry of Foreign and European Affairs and the Ministry of the Economy, Finance and Industry, in charge of mining. It draws upon six specialised centres.

CESEV, the Centre for Advanced Studies in the Exploration and Exploitation of Mineral Resources, is based at ENSG Nancy. It offers a 9-month course in the field of mining exploration and ore exploitation projects. The industrial project developed during the course is the opportunity to explore in-depth a specialisation of interest to the trainee and his company.

CESTEMIN, the Centre for Advanced Studies in the Treatment of Industrial Evolutions and Mutations, was developed to meet the growing demand of many areas of the world confronted with the need to modernise and restructure their heavy industries and to create new ones, taking into account the constraints of sustainable development. This course was awarded the title of Specialised Masters by the *Conférence des Grandes Écoles* in 2002.

CFSG, this training course specialised in geostatistics within the Mines Paris-Tech group is intended for mining industry professionals. It is a 9-month postgraduate course open to engineers and geologists interested in acquiring knowledge of geostatistics and all its areas of application.

CESPROMIN, the Centre for Advanced Studies in Mining Projects, founded in 1990, offers studies in the field of economic evaluation of mining projects.

CESCO, the Centre for Advanced Studies in Quarry and Open-pit Mining, founded in 1985, is geared towards mining engineers and geologists who wish to perfect their knowledge and skills in this field. The course is taught in alternate sessions in French and English.

CESSEM, the Centre for Advanced Studies in Mining Safety and the Mining Environment, is hosted by the *École des mines d'Alès*. It offers a course in safety enforcement in mining and mining environments, as well as in legislative and regulatory aspects. The course ends with a 12-week individual study project.

CESAM, the Centre for Advanced Studies in the Public Administration of Mines, aims to train mining industry executives on the State's role in the exploitation of natural resources. It is geared towards mining engineers, geologists, legal experts and high ranking civil servants within mining administrations. This 6-month course ends with a 6-week personal project. It is based at Mines Paris-Tech.

Specialised Industrial Courses

ENSPM-IFP School

IFP School is run by the French Institute of Petroleum-New Energies and offers applied graduate programmes, providing students from all over the world with education to meet the needs of industry in the fields of oil, gas, energy, petrochemicals and powertrains. In 2008, IFP School offered 18 programmes to over 400 students, including vocational courses in the field of geosciences.

ENAG

Founded by BRGM on the model of the Higher National School of Oil and Engines (ENSPM) for the oil industry, the National Applied School of Geosciences (ENAG) aims to meet the training needs of the main public and private players in the sectors of mineral raw materials, geothermal energy and CO_2 storage. It offers a 1-year post-Masters course in Orléans at BRGM and aims to qualify specialists (university diploma), to the highest levels of strategic and operational responsibilities, in order to join companies and public services of the States and organisations concerned.

International University Courses

ISTO-UQAM

An international Masters in exploration and management of mineral resources (EGERM), jointly awarded by the University of Quebec in Montreal (UQAM) and the University of Orléans, offers teaching in the fields of metallogeny, exploration and sustainable resource management as well as in the geodynamics of the lithosphere (Géologues 2007). Third semester classes take place partly at UQAM in Montreal (4 months) and partly in the field, with excursions in this area of the world that is very active in terms of mineral resources (13 % of GDP in Quebec).

Abitibi Field School, Quebec

An international school in the geology of mineral resources, referred to as field geology in the North American context, was founded in 2008 in the province of Abitibi in Quebec. This course is developed in partnership with Quebec's Ministry of Natural Resources and Wildlife (MRNF), the University of Quebec in Abitibi-Témiscamingue (UQAT) and the Higher National School of Geology in Nancy (ENSG). Accepted candidates are Masters level university students (Toulouse, Rennes, Lille, Poitiers, Orléans, Grenoble and Nancy) and the course is coordinated by ENSG Nancy.

This initiative aims to reinforce training in the field and in mining companies interested in exploration for mineral raw materials. It has met with great success since its launch (2008), both from a point of view of students and partner businesses, with many students being recruited in Canada, France and Western Africa. It responds well to the training needs at this time of increasing demand for human resources alongside the rise in raw material prices.

Finally, it is complementary to the courses offered by French universities, thanks to a practical course in the North-American geological and metallogenic context, in particular that of volcanogenic massive sulphides, including at sea. The features studied are comparable to current major exploration and mining areas (Western Africa, Australia, South Africa, Baltic Shield, Siberia and Brazil in particular).The 4-year groups (2008–2011) having taken this course so far comprise 44 students, of which 37 were French and seven Moroccan.

The course syllabus is structured around field geology techniques applied to mining exploration: regional geology, health and safety, geological surveys, routes and positioning, submarine volcanism and volcanogenic massive sulphide deposits, structure, sedimentation and gold deposits, plutonism, geophysics applied to geological mapping and mining exploration, quaternary geology, logistics, communication.

LabexMer, Marine Excellence Research

LabexMer, recently selected as an "initiative of excellence", reinforces the research, teaching and innovation potential in the field of marine sciences in Brittany. This centre, run by IUEM in collaboration with CNRS, IRD and Ifremer, comes under the University of Western Brittany (UBO) via the research and higher education cluster for Brittany.

One of Labex's research priorities directly concerns marine mineral resources, through the genesis and structure of hydrothermal sites and the associated sulphide deposits. This centre also deals with training, in particular with international scope, with short courses on offer to Masters and PhD students, as well as professionals already in the job market.

Conclusion

Today France has a remarkable research capacity in the field of geosciences. Thanks to the excellence of its research teams and the availability of high quality analytical platforms, it boasts internationally renowned expertise in the field of mineral raw materials. The scientific value of research relating to the formation of mineral deposits (including deep-sea deposits) is internationally recognised. The federative action taken by INSU, alongside the ANCRE Alliance, in particular aims to boost synergy between the players of this community (universities, public industrial and commercial establishments (EPIC), public scientific and technical research establishments (EPST) and industry). The incentive actions launched by CNRS (CESSUR-INSU, GUTEC-PACEN) are designed to support coordinated actions to supplement other programmes such as Marge-INSU or Mistrals-Termex via foresight workshops and theme-based schools. These initiatives need to be strengthened and sustained, with the support of new funding programmes, like at the French National Research Agency (ANR) where an initiative devoted to raw materials and in particular marine mineral resources is highly desirable.

In terms of training, France has an effective offer in Earth sciences that completely covers the range of qualifications (technical diplomas, university diplomas, degrees, Masters, engineering schools, specialised industrial and university courses, PhDs). Furthermore, these courses are present across the whole of the national territory through a network of 35 universities and 48 Masters courses, enabling complete exposure of the training offer and facilitating recruitment of students interested in the new societal developments of Earth and environmental sciences, encouraged by the emergence of diversified pathways characterised by high geographical mobility.

The international courses are entirely complementary to this offer, with emphasis on the reinforcement and development of existing structures (such as CESMAT), to meet the foreseeable increase in international demand. As concerns this foresight study on marine mineral resources, the various courses in Earth sciences all offer good skills in the basic disciplines of geosciences, with training opportunities through specialised marine geoscience courses.

The job market in the field of geosciences is rapidly picking up. As for the academic sector, public industrial and commercial establishments (EPIC) and public scientific and technical research establishments (EPST), the replacement of retiring executives is in progress, whether at BRGM, Ifremer or CNRS-INSU for instance, with several recent job offers for geologists. The industrial job market in this field is also picking up, as attested by the growing success of Masters courses in resources (Toulouse, Rennes, Orléans, Montpellier, Grenoble) and engineering schools offering specialisations in the field of geological and mining engineering.

In France, Earth sciences, including marine geosciences, react to societal and industrial demand that has recently emerged in the field of mineral raw materials. Due to the urgency imposed by current international economic affairs, the effectiveness of training in these areas can yet be further improved.

Several avenues are possible: firstly, by encouraging networking between different research and research and development players; secondly, by continuing efforts to structure the training sector, to respond to increased employment in this sector; finally by providing a wider, attractive international training offer for economic players (corporate executives and geologists), in particular in the form of short courses.

Chapter 8
Access to Raw Materials

A Historical, Legal and Geopolitical Vision

Antoine Valéry

Introduction

The importance of raw materials in human activities, their non-renewable nature and the gradual exhaustion of easily exploited resources have become, over the past years, a major concern for many States, as well as the international community. As highlighted by Jean-Yves Perrot, Ifremer's Chief Executive Officer, "*growing tensions are appearing between mineral availability and global requirements, especially in industrial countries, which continue to rise in number and force (...). The foreseeable rise in demand, related to world population growth and the rising standard of living in developing countries, considerably reduces the estimated lifespan of metal reserves*." Access to raw materials today is a geostrategic challenge.

Yet "*Natural resources tend to be concentrated in relatively few locations around the world. This makes for profitable trading opportunities among nations. At the same time, because natural resources are so crucial to many economic activities, adequate access to them is regarded as a vital national interest everywhere. Those who possess natural resources may not always wish to trade them, but rather to harness them domestically as a basis for economic development and diversification*." (World Trade Organization [WTO], World Trade Report 2010 "Trade in natural resources", p. 3).

This observation by Pascal Lamy, WTO Director-General, accurately reflects the current challenges of this reality. Furthermore, the fact that, in 2010, the WTO devoted its annual report for the first time to trade in natural resources, described as a "challenge for global governance", is in itself an indication of increasingly acute tension in a field which, until then, did not fall within the natural scope of this organisation's concerns.

The same goes for the work of the G20 and in particular the Pittsburgh Summit, at which leaders agreed to "*improve the regulation, functioning and transparency of financial and commodity marketsto address excessive commodity price volatility*",

---

A. Valéry (✉)
French Institute of International Legal Experts, 94, boulevard Flandrin,
75116, Paris, France
e-mail: antoine.valery@gmail.com

Y. Fouquet, D. Lacroix (eds.), *Deep Marine Mineral Resources*,
DOI 10.1007/978-94-017-8563-1_8,

the Seoul Summit in November 2010 and the report of the Task Force on Commodity Futures Markets. Free trading is, for raw materials too, a guarantee of supply security.

Yet, threats to this freedom and, therefore, to the supply of natural resources, tend to accumulate. However, certain reactions are beginning to emerge and perhaps foreshadow, in different ways, a future form of international regulation.

Threats Towards Access to Raw Materials

These Threats Arise from Various Types of Concentrations

Firstly, the geographical concentration of the production of many essential raw materials.

Such concentration can of course be due to the scarcity of metals which are only found in certain deposits, but it can also be caused by industrialised countries' prolonged disinterest in certain materials, such as rare earths (which, contrary to their name, are in no way rare), or by the upstream to downstream control of a metal by a State, as is the case of China for tungsten[1].

Over and above rare earths (95 % in China), we can also make mention of examples such as niobium (90 % in Brazil of which 80 % belongs to the family-owned business CBBM), rhodium (77 % in South Africa) and germanium (75 % in China)[2].

Furthermore, over 50 % of raw material reserves are located in countries whose national income per capita is less than or equal to $ 10 per day, countries which often suffer from institutional instability leading to consequences such as legal insecurity, but to which mining operators increasingly turn for asset acquisition given growing demand for raw materials[3].

Secondly, a concentration of operators.

Figures prior to the 2008 crisis already spoke for themselves: in 2005, 762 mergers and acquisitions had been identified, totalling $ 69.9 billion. Two years later, this had risen to 1,732 mergers and acquisitions totalling $ 158.9 billion, resulting in the creation or reinforcement of major firms, representing alone the majority of the total value of mineral production and therefore able to impose their terms on the markets. In 2008, these companies represented 83 % of the total value of mineral raw materials production, while the top ten non-energy mineral operators represented 32.69 % of global production[4].

While we have not yet completely reached 2007 levels again, mining groups have, following the 2008–2009 crisis, resumed their race for acquisitions. 1,123 transactions for a total value of US$ 113.7 billion were recorded in 2010, compared

---

[1] Cyclope 2011, p. 534.

[2] Cyclope 2011, p. 534.

[3] Cyclope 2011, p. 534.

[4] Cyclope 2011, p. 534.

to US$ 60 billion in 2009, giving an 89 % rise[5]. China's share of asset purchases, which represented 24 % of global acquisitions, lagged in 2010 (11 %)[6]. Such a concentration clearly has a considerable impact on the price setting mechanism.

Thirdly, a concentration of power in the hands of certain States. How, once again, could we not mention China and the control it directly exerts on its own raw material resources? Yet, as we know, it possess the majority of some of these exploited materials, such as rare earths, with 130,000 of the 133,600 t produced worldwide in 2010[7]. It thus controls practically the whole world market for this resource, deciding at what price, but also to whom, it shall be sold. We can fairly easily, given the circumstances, imagine both the legal and economic consequences of such a position.

Bolivia is another example, notably with its lithium reserves, whereby the new Constitution of 25 January 2009 states that its natural resources are the indivisible property of the Bolivian people and are administered by the State[8].

Yet such evolution towards a concentration of power in the hands of States today constitutes a very marked trend in many producer countries.

These Threats are also Generated by the Reappearance of Judicial Nationalism

This judicial nationalism is found in various forms.

By the Reappearance or Reinforcement of Legal and Tax-Related Obstacles

We note that in 2009, the European Commission recorded no less than 450 export restrictions on over 400 raw materials. This shows the extent of the phenomenon which is illustrated by mechanisms such as quotas, exportation rights and various systems designed, whether openly or not, to restrict the access of foreign mining operators, whether in capitalistic or operational terms.

By the Establishment of Protectionism

It is worth remembering in this respect that the Chinese 2009–2015 provisional plan went as far as including an outright ban on the exportation of certain rare earths whose importance is well known, in particular for electronics, computers, telephones and other technologies. We can only imagine the consequences such a ban could have had. The fact that China dropped its plan following Japan's complaint to the WTO shows that the use of legal instruments, which will be addressed below, or even the prospect of their use can have a dissuasive effect.

---

[5] Cyclope 2011, p. 534.

[6] Cyclope 2011, p. 534.

[7] Cyclope 2011, p. 534.

[8] Cyclope 2011, p. 534.

Yet, not content with attempting to restrict extraction of rare earths to the country's own needs, China is seeking, for other materials such as nickel, to limit extraction below its own needs. It prefers to preserve these materials as future currency both for trading, economic and financial purposes, even if it means buying the lacking quantities on the international market, which will naturally have an impact on prices.

By the Constitutionalisation of Mining Law in Certain States

This is a major change which affects mining law in many countries around the world and of which Europe perhaps does not always realise the importance.Unlike European States in which mining law is governed by "ordinary" laws, major producer countries have constitutionalised this law. This is the case for instance in Brazil, Columbia, Cuba, Indonesia and the Dominican Republic.

In Bolivia, it is striking to see that it is the new Constitution which determines the content of mining law (investments, prospecting and exploration, exploitation, concentration, industrialisation and trade), while the "ordinary" mining law, similarly to what in France we might call an implementing decree, should only define the scope of this law[9]. The strategic importance of the mineral resource is laid down by the Bolivian Constitution itself[10].

This provides a significant indication of the importance that these States grant their mineral resources and goes hand-in-hand with the visible "ascension" of mining law in the hierarchy of standards.

First Steps Towards an International Legal Order on Raw Materials

Awareness of these threats is relatively recent and reactions have been gradual.

European Awareness

This awareness can be attributed to the European Commission and its 2008 Raw Materials Initiative[11] following which an expert report was published in 2010 listing fourteen critical mineral ores and metals among the forty-one studied. In its communication of 2 February 2011 entitled "Tackling the challenges in commodity markets and on raw materials"[12], the European Commission emphasised the issue of price volatility as well as the correlation between commodity markets and financial markets.

---

[9] Article 369, paragraph I and 370, paragraph IV of the Constitution.

[10] Article 348, paragraph 2.

[11] COM (2008) 699.

[12] COM (2011) 25.

Its main principles, in addition to monitoring critical raw materials, are ensuring fair and sustainable supply from global markets (pillar 1), fostering sustainable supply within the European Union (pillar 2) and boosting resource efficiency and promoting recycling (pillar 3).

Emergence of Raw Materials Diplomacy

According to the European Commission, the European Union "*should actively pursue raw materials diplomacy with a view to securing access to raw materials*". Yet, in the field of nuclear energy in France, nuclear advisers can already be found for certain French embassies (US, Russia, Japan, China, Korea, EU).

We may at present consider whether it would be appropriate, like Japan, to create "raw materials" advisers for embassies or delegations of the European Union in producer countries. The role of such advisers would be to monitor in real time the industrial, economic, commercial and legal evolution of raw materials, with rapid transmission of information enabling shorter reaction times.

Similarly, why not grant France's new Committee for Strategic Metals (COMES), created by the decree of 24 January 2011 following the action plan to secure France's access to rare mineral materials announced on 27 April 2010, powers of intervention analogous to those of its Japanese equivalent, JOGMEC, which recently announced deals with the Australian company Lynas (rare earths) and the Brazilian company Mineraçao (niobium)?

International Awareness

This issue of raw materials supply does not leave the international community indifferent. In particular, we can make mention of the African Mining Vision 2050 adopted in 2009, as well as the Extractive Industries Transparency Initiative (EITI) established in 2003, and the entry on 1 March 2011 of eleven new members having made significant efforts in terms of transparency (including Central Africa, Niger, Nigeria, Ghana as well as Yemen, Norway and Azerbaijan) (see Fig. 8.1).

Yet it is no doubt the intervention of the WTO that constitutes the most decisive factor of the past years. Mention has already been made of the efforts implemented by this organisation to address its role in the raw materials market, with fair access to these resources now constituting, as far as the WTO is concerned, a prerequisite for State competitiveness, given the increasingly fierce international competition they generate[13].

However, things have not been left at the reflection stage. On 23 June 2009, a European request for consultations was submitted to the Chair of the WTO Dispute Settlement Body (DSB)[14] concerning Chinese measures related to the exportation

---

[13] Ifremer 2011. Les ressources minérales marines profondes. Prospective à l'horizon 2030, p. 36.

[14] Ifremer 2011. DS 395.

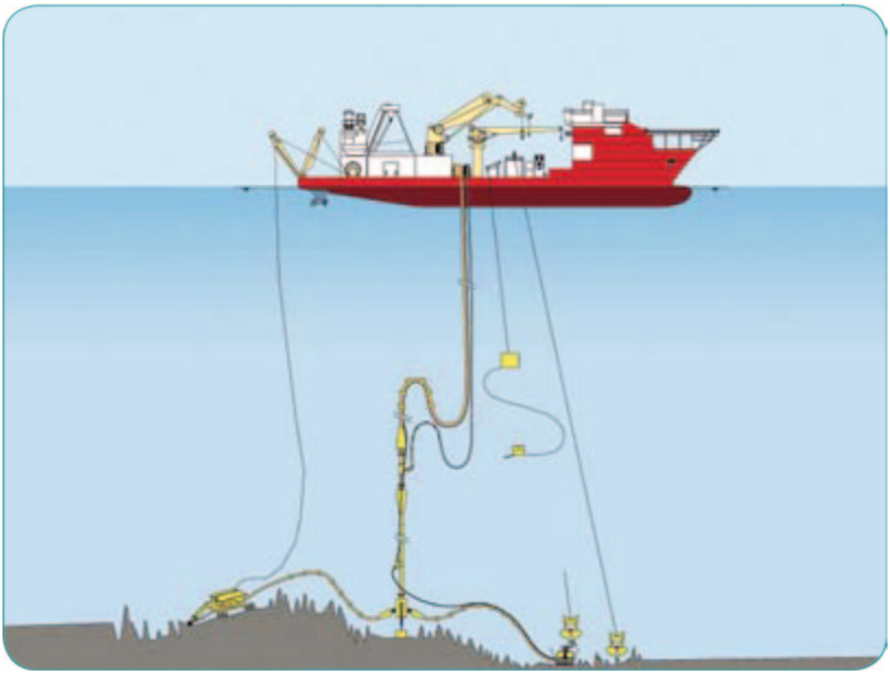


Fig. 8.1 Diagram illustrating deep-sea sulphide mining

of various raw materials (bauxite, magnesium, manganese…); the United States and Mexico made similar requests[15].

However, according to the Panel Report issued on 5 July 2011, the panel established by the DSB to examine these disputes noted the incompatibility between China's exportation rights and the commitments it made in its Accession Protocol, as well as the incompatibility between the export quotas it has imposed for certain raw materials and the rules of the WTO. It is also worth noting that while China decided, in December 2010, to cut its rare earth export quotas by 35 % in the first quarter of 2011 (compared to the same period in 2010), it then decided to double them for the second quarter of 2011[16].

Over and above these observations, it is clear that issues relating to raw materials now fall within the competence of the WTO.

However, effective regulation requires a control and enforcement system, somewhat like what has been introduced offshore by the United Nations through the United Nations Convention on the Law of the Sea of 10 December 1982 with the ISA and its international tribunal.

Yet for onshore resources, the issue is even more delicate as it challenges State sovereignty, and only strong political will can enable such a change.

---

[15] DS 394 and DS 398.

[16] Les Échos, 15 July 2011.

Chapter 9
Conclusion

Yves Fouquet and Denis Lacroix

The many foresight studies on the world's situation by 2030, with the exception of "disasters", provide a number of robust contextual elements for this time frame. In 2030, nearly two thirds of the world population (over 8 billion) will live in Asia. Europe with its 27 member countries, characterised by strong population ageing, will only account for 6.5 % of the world population. Half of humanity will live in cities and the "rich/poor" and "old/young" divides will deepen.

In economic terms, while the United States will continue to have the world's leading economy, Asia will surpass the European Union with 30 % of world trade and will take scientific and technological supremacy. India and China will represent 20 % of world research, compared to 10 % in 2008. Knowledge and key technologies will relate to sustainable development (especially energy), adaptation to climate change, health, security, including food security, and social sciences. The convergence of recent technologies (nano and biotechnologies, IT, communication) will generate revolutions in all fields, hence a major role for science in the structuring and rapid evolution of societies. Pressure on materials and metals (copper, rare earths…) is set to rise, in connection with electronics: in 1980, an electronic chip contained 10 metals, today it contains 60! Renewable energies are also set to consume large quantities of these rare metals.

One of the major challenges will therefore be access to mineral resources due to the generalised rise in demand (in particular mineral ores) and the risk of damage to the ecosystems affected by mining. All major countries, including France, are now confronted with the question of the security of their "strategic" minerals supply. Risks of "economic wars" on resources already exist, as revealed by the recent rare earth availability crisis on the global market, of which China holds a 95 % share.

Y. Fouquet (✉)
Centre Bretagne, Laboratoire Géochimie Métallogénie,
Ifremer, CS 10070, 29280 Plouzané, France
e-mail: yves.fouquet@ifremer.fr

D. Lacroix
Station de Sète, Ifremer, avenue Jean Monnet, CS 30171,
34203 Sète Cedex, France
e-mail: denis.lacroix@ifremer.fr

Y. Fouquet, D. Lacroix (eds.), *Deep Marine Mineral Resources*,
DOI 10.1007/978-94-017-8563-1_9, © Éditions Quæ 2014

A national and European policy in terms of access to strategic minerals is not only justified in the medium term, but has become urgent given the implementation times required. Growing dependence for strategic metals is expected to have negative impacts both in economic terms and in terms of security and sustainability for many sensitive industries, in particular in the military field.

France has many assets in the field of mining (scientific and technological research, mining industry, metallogenic treatment, offshore engineering, training…) and boasts large maritime areas whose exploration is gradually revealing various mineral resources.

This study on deep-sea mineral resources has therefore called upon targeted foresight to answer guiding questions in terms of scientific knowledge, exploration and exploitation technologies, socio-economic profitability conditions and predictable impacts on the deep-sea environment.

Five major areas of action emerge as priorities if France is to preserve the security of its strategic mineral supply and reinforce its action capacities in this field.

In scientific terms, it is crucial for new deposits to be discovered and knowledge of deep-sea mineral-rich sites to be improved, starting with the understanding of metal transfer and concentration processes. This exploration should take into account ecosystems associated with these geological features, in order to estimate biodiversity and determine their vulnerability if subject to mining in situ or close by.

In technological terms, it is important to note that, while these deep-sea exploration technologies exist, they could be greatly improved upon, as they must be adapted to these new geological contexts. Mining technologies still need to be developed and tested. The major challenges and high costs involved justify the need to reinforce this French industrial sector and to build it on a wide-reaching pan-European partnership.

In geopolitical terms, the question of access to areas of interest should be addressed both on a national scale (exploration, exploitation and extension of the continental shelf through the Extraplac programme) and an international scale: upkeep of nodule licenses, submission of new applications, diplomatic actions in international management bodies… Growing global competition for access to maritime areas is a certainty.

In political terms, several actions should be carried out jointly, such as the growth in economies consuming sensitive metals and the study of their substitutability and their recycling as part of an eco-design approach. This policy should be planned and coordinated with all players, both within the metal industry and the fields of end use, in order to save time, improve efficiency and reduce the resources required.

In environmental terms, the considerable lack of knowledge on deep-sea ecosystems, which are far richer and more diverse than initially expected, must first be overcome. Through such exploration, the constraints on exploitation may be defined in order to minimise impacts and marine protected areas may be proposed, in order to guarantee a long term balance between exploitation and protection.

France has assets in all the fields involved in the development of deep-sea mineral resources, starting with the first of all: available space. Yet the world is entering a phase of growing tension over these resources. It has therefore become necessary in this field to prepare a controlled, rather than an imposed, future.

Appendices

Appendix 1—Study Methodology

Study Framework

The pivotal question of the study is that of evaluating the potential of the main deep-sea mineral resources (metal ores and natural hydrogen) that represent a strategic goal for France and the European Union for 2030.

This initiative aimed to answer three main questions on these resources by 2030: what scientific and technological knowledge is required for their discovery and exploitation? What socio-economic conditions are liable to make their exploitation competitive? What environmental impacts of their exploitation can be foreseen?

In terms of methodology, the analysis drew upon the representation of the studied system (global environment, review of current scientific knowledge, sectors, challenges for stakeholders) before exploring possible evolutions of major variables, followed by the conditions required to harness the potential of these resources. It was therefore possible to identify the dynamics relating to the main sectors and draw lessons in order to define action proposals, including a national research and development programme.

The ten working meetings, as well as the three Steering Committee meetings, were planned over ten months, which facilitated the continuity of efforts and progress monitoring. These meetings were held between 30th September 2009 (first Steering Committee meeting) and 7th July 2010 (last Steering Committee meeting). The Working Group also heard fourteen experts to improve its knowledge of the subjects studied.

Specificities of the Approach and Chosen Study Arrangement

In most prospective approaches, the parameters closest to the subject are the most accurately defined and most well-known. Major uncertainties are often associated with aspects relating to the overall context and the involvement of stakeholders in the sector. In this case, this situation is largely reversed: the least known, and most uncertain, phenomena are the marine mineral resources themselves and their

Y. Fouquet, D. Lacroix (eds.), *Deep Marine Mineral Resources*,
DOI 10.1007/978-94-017-8563-1, © Éditions Quæ 2014

development (especially potential changes within the system studied). The following specificities therefore guided the choice of prospective approach and the progress of work.

Development of Marine Mineral Resources: A High Level of Uncertainty

First of all, the study approach has to make the best of emerging knowledge of marine mineral resources and their environments, dealing with their location (with the relative exception of nodule zones), the intrinsic variability of their mineral wealth (cf. Chap. 3 of Part 2) and the biological wealth of sites. The creation of a common language between those involved (research, research and development…) on the state of knowledge appeared as a prerequisite for the improvement of scientific knowledge, in particular via the notion of inventory.

Furthermore, the analysis of the relative economic values of the metals contained in marine mineral resources and the strategic interest of mineral resources by type of metal require at least two in-depth foresight studies that were not available at the time of this work[1]: one on the medium and long term appreciation of strategic metals for France (economic, geopolitical, defence-related aspects… according to resources and uses, and substitution possibilities[2]), and the other on land-based mineral resources and the recovery possibilities by metal type. Prospective investigation of these aspects was thus conducted taking into account existing foresight analyses on a European or global scale with the Organisation for Economic Co-operation and Development (OECD), analyses which only partially meet the requirements and show divergence according to the criteria used. Certain criteria were documented indicatively by members of the Working Group, until a more in-depth study on strategic metals can be carried out.

Finally, the potential exploitability of resources is not demonstrated for all aspects (economic, technological, environmental). In terms of technological capacities, the functional capacity of modules required for exploitation taken individually (collection from the seabed, techniques for bringing minerals to the surface, material management on vessels, transport, processing…), which are available and require only minor adaptations, should be distinguished from the development of a complete system, on medium and large scales, incorporating these various modules and subject to all possible risks, which currently remains at the stage of a pre-demonstrator (for hydrothermal sulphides and nodules; no projects for crusts).

To summarise this first point on marine mineral resources, the necessary knowledge (scientific, technological, biological) remains partial, often specific and localised. Generalisations are therefore risky and controversies high.

---

[1] Launched in early 2011.

[2] For instance, substitution between metals within the platinum group for many of their uses.

Regulatory Context and Stakeholder Involvement: Rapid Changes Requiring Immediate Responses

Variables relating to the context, stakeholder involvement, scientific and technological alliances and partnerships are evolving rapidly (the coming five to ten years will be decisive), and the international regulatory framework for exploitation is likely to be established in the coming years (negotiations in progress, applications being submitted for international waters for hydrothermal sulphide sites).

These short and medium term changes in the context require a national stance, and short term arbitration on certain questions (permits, alliances, demonstrators…) in a situation of scarce resources (human, technical and financial). Geopolitical and economic challenges are therefore high. Sharing of or access to scientific knowledge on the potential wealth of certain sites by stakeholders (States, economic players) is by no means neutral.

Changing Global Context: Major Trends and Global Scenarios

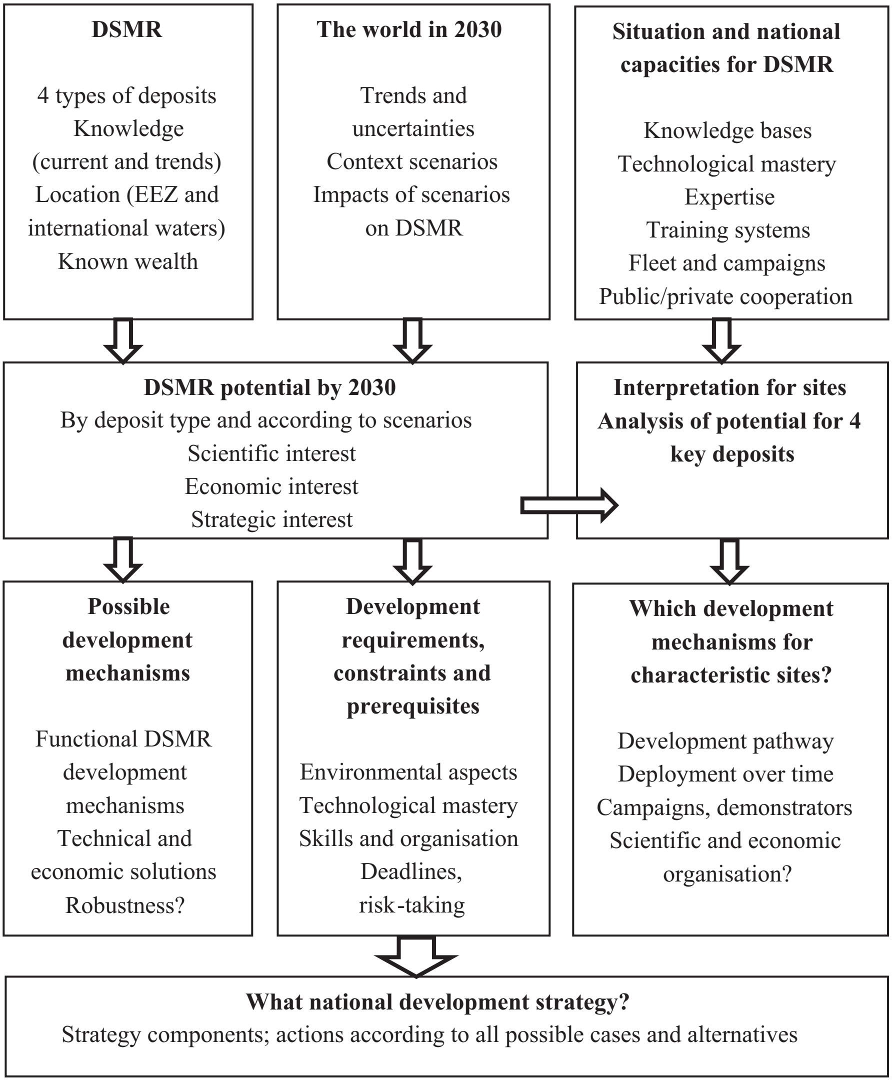
Unlike many long term foresight studies on resources (energy, agricultural resources…) for which changes in the global context are determining factors, the salience of global changes in the study of marine mineral resources is indirect and sheds little light on medium term choices. For instance, growing and lasting global tension over certain metals, related to a limited supply and high demand, in a context of restricted access (situation of rare earths in the medium term), leads first to increased value or exploitation of neglected land-based resources, progress in terms of supply diversification by users and efforts in terms of recovery and substitution where possible.

These adaptations occur within time frames of five to ten or fifteen years. However, the development of marine mineral resources, over and above the hypothetical nature of its capacity to respond to these tensions, is envisaged within a time frame of fifteen to twenty years… thus beyond that of adaptations to land-based resources. This means that global changes taken into account do not shed light directly on the long term exploitation of marine mineral resources. They mainly provide information on the national context and stakeholder involvement.

Considering the possible futures for 2030 remains conceivable, yet the construction of trajectories for the national strategy is a more delicate task. For this reason, the scenario-building work was restricted to three avenues: global changes, context of marine mineral resources (stakeholder involvement) and conditions of development of a national strategy.

Between the strategic gamble on the future and the option value, the joint work prioritised the second approach. This consisted of studying the provisions that leave the future open to the development of marine mineral resources, in fields which appear liable to generate the most value, in the widest sense: economic, ecological and heritage value. Classic prospective techniques (variable by variable analysis, scenarios method, impact of scenarios on the subject, challenges, possible trajectories) are able to deal with “risky environments” (several possible states, comprehensive

Table A.1 Function block diagram of the study (source: Gerpa)



sets and objective probabilities) or “uncertain environments” (several possible situations, more or less comprehensive, subjective probabilities). They are also able to incorporate major trends, as was the case for changes in the environment and context. As for the development of marine mineral resources, work focused on the pooling and comparison of knowledge and prospects within the group and with various players met, through an inductive approach (from the heart of the system to its environment and not the opposite): investigation of the characteristics of marine mineral resources, understanding of the conditions and context of their development, integration of global phenomena (cf. Table A.1).

The working method is broken down into five points:

- What are we talking about?

Objectives: outline the system; build a common language on marine mineral resources (expertise, relative certainties, uncertainties).

- The development potential of marine mineral resources by 2030

Objectives: put forward an interpretation of the strategic challenges for the main metals; take into account the range of interests in marine mineral resources: economic, heritage, scientific, geopolitical; evaluate their attractiveness and the associated challenges.

- The development context of marine mineral resources by 2030

Objectives: there are three main objectives. Firstly, to take into account changes in the legal, economic and geopolitical environment that affect access to the potential of deep-sea mineral resources; hypotheses and scenarios. Secondly, to identify environmental, technological and scientific requirements, constraints and drivers. Thirdly, to combine global scenarios, the context of action and associated challenges for the national development strategy.

- Possible development mechanisms and requirements

Initially, for each type of deposit, to analyse useful functional aspects (research, demonstrators, equipment, expertise, infrastructures…) and their potential. Thereafter, to evaluate the interest and feasibility of mechanisms according to the degree of preparation of national players (research, industry) and several additional criteria: costs and outlay, availability of technologies, organisational skills and know-how. For reasons of confidentiality, the results and contributions to this phase have not been presented.

- What strategy?

Principles and recommendations. Long term coherent framework, ambitions. How to: the strategy. Legal adaptations. Short and medium term commitment proposals, resources, organisation (partnership platform…).

In the final phase, the group restructured the results and their presentation in order to facilitate their operational use.

Main Points of the Method

Stage 1. What are we talking about? State of the art and knowledge During the framework definition phase, four types of sites and their associated resources were selected: cobalt-rich and platinum-rich crusts; hydrothermal sulphides; polymetallic nodules; natural hydrogen production sites.

The group first conducted an initial analysis of the mining potential of these sites by considering four types of interest: scientific, economic, strategic (supply security)

Table A.2 General framework of knowledge of marine mineral resources

Type Field of discussions	Hydrothermal sulphides	Cobalt-rich crusts	Nodules	Hydrogen
Scientific knowledge	+	+	++	+ Studies
Legal field, licenses/permits	ISA application in progress	Operational in EEZ; ISA application under preparation	++	?
Technologies for industry	Land-based exploitation in progress; 1 offshore project (Nautilus)	Exploration tools; no exploitation	++	?
Development conditions	High variability: sites, volumes, metals[a]	? Mainly for Co and Pt. Still only exploration	?	?
Environmental knowledge and constraints	Low; sites often biologically rich	Practically unexplored; under study (marine volcanoes)	Under debate	?
Socio-political sensitivity	?	High in French overseas territories	High in French overseas territories	?

[a] Cobalt, manganese, copper, zinc, tellurium, indium, titanium, ruthenium, gold, silver, platinum

and heritage (long term resources), with respect to current knowledge and conditions (Table A.2).

This knowledge was then systematically organised following discussions and contributions for each type of deposit, distinguishing known characteristics, relative certainties and major uncertainties. These analyses are summarised in the first chapter of this document in the section: "relative certainties and uncertainties" by deposit type.

Stage 2. The development potential of marine mineral resources by 2030 This stage includes two objectives: to put forward a strategic and technico-economic interpretation for the main metals present in marine mineral resources, from a multi-criteria analysis, taking into account the range of interests in marine mineral resources: economic, heritage, scientific, geopolitical, to evaluate their attractiveness and the associated challenges.

Multi-Criteria Analysis of Metals Present in Marine Mineral Resources

Existing analyses (European Union, OECD, United States) take little or no account of the substitutability of metals in their uses, the development of known land-based resources and the "recoverability" of metals. They mainly focus on an interpretation of supply risks (political and technical) and the medium term economic importance.

This work therefore focused, in this second stage, on taking into account complementary dimensions (evolution of land-based supply, substitutability…) and the

Table A.3 Framework of the multi-criteria analysis of metals contained in marine mineral resources

Metals Criteria	Base metals: Pb, Ni, Zn, Cu, Co…	PGMs	By-products: indium, gallium…	Rare minerals for specialised uses, such as rare earths
Demand dynamics				
Supply dynamics				
Rupture in land-based supply				
Price dynamics				
Uses and substitutability				
Geostrategic risks				
Metal concentrations on sites				
EEZ importance in France				
Relevance of mining				
DSMR potential				

investigation of specific aspects of marine mineral resources for each type of metal. Contradictory documents in the multi-criteria analysis table (Table A.3) required a major preparation effort, implemented by teams from BRGM and the French Ministry of Ecology, Sustainable Development, Transport and Housing, with their respective approaches, and called for several working sessions within the group, in the absence of a shared reference in 2010.

The two main observations at this stage in the study can be summarised as follows:

- The group retained the need for the diversification of specialised metal and alloy sectors. Mobile electronic devices, the aeronautical industry, the automotive industry and energy industries (oil cracking…) use increasing quantities of high-tech metals (tantalum for capacitors, gallium, germanium, indium…) and superalloys (cobalt, tantalum, niobium, rare earths, rhenium). Some of these metals of which very low volumes are used remain nevertheless decisive in alloys. Industry dependence on these metals has considerably increased, and there is nothing to indicate a decline in this dependence in the medium or even long term (twenty years).
- The "metal" risk has evolved with market globalisation, just-in-time supplies, insufficient or poorly managed recycling due to the miniaturisation of components and the number of high-tech metals involved. Many of these metals are in fact by-products of base metal refining (copper or zinc) in very low quantities. Production as by-products is inelastic and cannot meet strong variation in demand. This results in imbalances between supply and demand and recurrent crises. The fall of the Berlin Wall marked a period of reduced tension in terms of supply (influx of raw materials from former Eastern European countries). Low prices between 1995 and 2005 led to a major decline in mining investments over this period. Since 2006, prices have been on the rise, with the 2008 crisis only stalling curves by eighteen months.

Following this work, at the crossroads between strategic metals and the potential of marine mineral resources by deposit type, key metals in marine mineral resources

Table A.4 Assets of different types of deposits

Site type	**Interest**						**Weighted average**
	Value	Exploit-ability	Scientific	Strategic	Biological	Geopolitical	
Weighting	2	2	4	3	2	1	
Crusts	3	1	4	2	3	3	2.8
Sulphides	4	3	4	3	4	4	3.6
Nodules	2	1	2	1	3	2	1.8
Hydrogen	1	0	4	1	4	4	2.4

were determined, and divided into two types: type A, with base metals under probable economic tension (zinc, copper, manganese, cobalt, silver) and precious metals with a high heritage value (gold and, to a lesser extent, silver); and type B, with critical metals with a high technological potential and major supply risks (indium, germanium, gallium, related to zinc, on hydrothermal sulphide sites), antimony (to be investigated further), rare earths (in small proportions, back-up resource in the face of known needs). Furthermore, platinum and platinum group metals on crust sites (with uncertainty over substitution and usage—two hundred years of reserves today) are a specific case, given the wealth of French EEZs.

Attractiveness Analysis by Deposit Type

Following this multi-criteria evaluation focusing on metals and their relationship with deposits, a summary of the assets of different types of sites and deposits was produced. Six dimensions were considered for each deposit type (Table A.4):

- value of the mineral ore (intrinsic, excluding exploitation cost),
- exploitability based on technologies available in the medium term (2030),
- scientific interest of sites with respect to existing knowledge,
- strategic interest with respect to supply risks for certain metals,
- geopolitical interest given stakeholder involvement,
- quantitative evaluation from 0 (no interest) to 4 (maximum interest). Several weighting schemes were tested. In all cases, the sulphide sites are at the centre of all medium term challenges.

Development Conditions and Context for 2030

(Global scenarios, challenges and strategic questions)

The analysis the context of deep-sea mineral resource development by 2030 was divided into three stages: first, the study of exogenous and endogenous variables for six compartments of the global environment, then for the intermediate context and finally for the mineral resources themselves.

Table A.5 Distribution of system variables according to their position in relation to marine mineral resources

Exogenous variables	Endogenous variables (in DSMR)
Global framework variables	Place as resources
Globalisation and growth	Stakeholders
Global crises	Exploration and scientific collaboration
Regulation of international system	
NGOs and environmental issues (including perceptions)	Deposit exploitation
EU trajectory	Environmental impact of exploitation
Specific context variables	
Changes in pressure on resources	Mineral processing
Place of metals in the economy, criticality	
Place of the sea and safety at sea	
Legal aspects (ISA)	
Stakeholder involvement (States, mining operators)	
Supply, diversification, recovery and substitution policies	

Table A.6 The three major scenarios and their consequences on the marine mineral resource context

Global framework	Specific context
Crises and barriers Decline of multilateralism Heavy political tensions	Strategic metals related to defence, telecommunications… Less fluid markets. States' autonomous supply strategies and protection of their resources. ISA weak and conflicts over maritime areas
Cycles as usual Politico-economic cycles and Darwinism Economic factors predominant	Economic tension over base metals and other metals. Reinforced cooperation between States and economic players. Supply diversification policies. Maritime area seen as a resource potential. ISA under influence
Global crisis and coordinated responses Threesome: States, firms, NGOs Towards post-carbon	Energy transition, generalised recycling, miniaturisation. Multinational strategies for critical metals. Maritime area = new boundary. ISA reinforced; public/private/NGO partnerships

The system variables are distinguished according to whether they are general, and therefore wider-ranging than the marine mineral resource system (exogenous variables), or specific, because they are directly related to marine mineral resources (endogenous variables). This dual approach is presented in Table A.5.

The method consisted in cross-analysing the evolution of seventeen variables up to 2030 accordingto three contrasting macro-scenarios whose main determinants were as follows: markets, international trade, legal status of international waters, national and/or multinational interests and critical mineral supply security, impacts on the deep-sea environment, stakeholder involvement and social perception. These three scenarios and their consequences in terms of effects on the marine mineral resource system are summarised in Tables A.6 and A.7.

Collective appraisal of these variables resulted in the establishment of three scenarios contrasting in terms of global changes and context (presented in the fifth section of the summary in part one of this document).

Table A.7 Relevance of possible stances for the national strategy by scenario

Scenario Position	A. Economic crisis: conflicts United States China	B. “Go with the flow”; business as usual; cycles	C. “Reactive: top exit”; global crisis, collective responses
Skills cluster; technological development through partnerships	+	+	+
Knowledge, inventory and preservation strategy (sustainable development)	(+)	+/−	++
European umbrella and targeted research		+	++
Resource security strategy (supply, power) geared towards industrial sectors		+	
Open skill development stance	+	+/−	+

Finally, stakeholder involvement was analysed in the medium term.

With respect to the scenarios, the place of marine mineral resources was discussed and several non-exclusive stances for the national strategy were debated:

- a national position essentially targeting the reinforcement of a skills cluster in France and the development of national technological know-how (selective approach), possibly with allies,
- a strategy geared towards scientific knowledge for the purposes of exploration, inventory and preservation, with a strict approach to environmental issues and concern for the preservation of EEZs,
- a European stance, for all areas of European legitimacy (possibly ranging as far as the pooling of EEZs in the long term, a shared fleet, a joint agency…), driven by wide-reaching research: knowledge of environments, technical and economic aspects,
- a strategic and economic approach to marine mineral resources as resources to be managed, aiming to establish a development sector in the long term from exploration to exploitation,
- an open stance, aiming to make maximum use of national assets, skills and know-how.
- After analysing the challenges for each scenario and comparing the scenarios and possible stances, the options for the national development strategy were identified for each scenario.

Scenarios

Challenges for the National Strategy in Scenario A “Crises and Barriers, Political Tensions”

In a climate of growing tension, we observe reduced market fluidity, leading to the introduction of autonomous supply strategies in most major countries. States with an EEZ increase their control of potential deposits in these zones and restrict the choice of partners to the circle of their close allies. Consequently, the situation of marine mineral resources vacillates between “set-aside and harnessing”.

Challenges for the National Strategy

Marine mineral resources are seen first of all as a resource to be controlled within the EEZ, hence the following priorities: inventory of mineral resources in the French EEZ; definition of exploration and exploitation rules within the EEZ; seeking of agreements between States for potential deposits of strategic interest in international waters; implementation of a regional scientific and technological integration capacity, either as a European partnership or through a multilateral agreement (e.g. France-Germany-Russia).

Priority

Inventorying resources in the EEZ(s) becomes the priority of exploration campaigns.

Challenges for the National Strategy in Scenario B “Business and Cycles as Usual”

Economic stakeholders are in search of new sectors to maintain their competitiveness and their offer. States, as well as industry, implement supply diversification policies to preserve an operational mining sector. Marine mineral resources thus appear as a source of potential resources and power, as their access remains restricted to a small number of advanced countries. The ISA continues to grant approvals, but has no influence on the strategies of the major States (US, China, Russia, India, Brazil, major States of the EU…). Consequently, the mineral resource situation is that of a “competitive-approach economic resource”.

Challenges for the National Strategy

Marine mineral resources are seen as an economic resource to be developed. This implies, in the long term, developing a full-fledged sector, from exploration to exploitation.

This “competitive” approach imposes the need for good knowledge of deposits in order to be able to select the richest, hence the following priorities:

- implementation of exploration and exploitation PPPs between States and private operators(French/European),
- management of private/public transfer,
- development of a mining sector (France-EU),
- support to European economic and technological stakeholders (pilot),
- sale of know-how and expertise by maintaining higher education skills.

Priority

The main objective remains to be scientific exploration campaigns to inventory resources, both in the EEZ and international waters, while preparing suitable partnerships to establish pilot(s), then exploitation.

Challenges for the National Strategy in Scenario C "Global Crises"

Within the context of the global crises scenario, it is in industrial operators' interest to seek multiple partnerships to reduce research and development costs and secure their markets according to international standards.The deep sea therefore appears as a sort of "new resource boundary", subject to strict exploitation rules. Consequently, the marine mineral resources situation becomes that of a "global heritage reserve, liable to measured exploitation".

Challenges for the National Strategy

The first challenge is that of achieving good scientific knowledge incorporating durability criteria. The second is that of shared, international exploitation, targeting critical metals (post-carbon), hence the following priorities:

- establishment of exemplary development and protection solutions (resilience, marine protected areas…) for French operations,
- resolutely European approach to development,
- creation of a training, technological expertise and engineering centre,
- increasing number of PPP-NGO ventures,
- support policy for marine protected areas in the EEZ.

Priority

This ambitious vision requires French then European means in terms of knowledge of deposits and their environment to be concentrated within a visible centre, before putting forward sustainable exploitation methods.

Which Strategies?

The guiding principles were distinguished by mineral type and associated site. Beforehand, a summary of the key messages of all the work was drawn up.

Five fundamental principles (relevant in all cases) were identified, following an investigation into relevance and priorities conducted among members of the Working Group and Steering Committee. These principles are therefore not contingent according to the scenario.

Priority 1: inventory and further investigation of the potential of marine mineral resources

- Joint PPP-NGO, multidisciplinary research (metallogeny, biodiversity, site resilience…).
- In interaction with national research into mineral resources.
- For EEZs: by prioritising cooperation with certain European States (or as PPPs).
- For international waters, in partnership with certain States (Russia and Germany for programmes already in progress).

Hence the need for two campaigns a year to make progress in the inventory (EEZ) and knowledge of characteristic sites (Central Atlantic, Southern Pacific…).

Priority 2: development of French technologies and industries

- Implementation of new exploration technologies: high resolution, three dimensional analysis, modelling.
- Research on certain aspects: corrosion, reliability, impacts…
- Need for a demonstrator to validate the integration of known yet complex technological solutions.
- Mineral processing: adaptation to ocean mineral ores.

Priority 3: development of a French cluster on deep-sea resources

- Integrated approach (cf. Grenelle Environment Round Table).
- Association of universities and schools, public research bodies (including life sciences research such as the French National Museum of Natural History) and private research organisations (Eramet, Areva, Technip…). This evolution could lead to the creation of a Thematic Advanced Research Network.
- Maintenance of skills in the field, development of coordinated training courses (open to international students).

Priority 4: heritage management of marine mineral resources in EEZs, Extraplac

- Prerequisite: general inventory for planning.
- Access to resources: clarification of access to marine mineral resources in EEZs (extralateral right, financial transparency).
- Definition of exploitation protocols for marine mineral resources in EEZs.
- In terms of flora and fauna: development of marine protected areas in EEZs (at least 20 % of the total surface area).

Priority 5: maintenance of French access to research in international waters (exploration licenses)

- Maintenance of the “nodules” license in coordination with Germany.
- Application for at least one exclusive research license on sulphide sites.

The proposals and guiding principles related to these priorities were reintegrated into the three major scenarios and are detailed in the study summary chapter.

Hydrothermal sulphides The exploration and potential exploitation of hydrothermal sulphides will be the pivotal point of all challenges: geopolitical (for international waters) within the framework of the introduction of ISA permits; environmental, with probable conflicts over site protection and exploitation conditions; scientific (volcanic and tectonic processes, rock and fluid geochemistry, specific metallogeny, biological resources…) and economic.

Crusts The exploitation of crusts will not come to fruition before 2030 (uncertain exploitability, technological availabilities…) despite their high potential. However, the richest areas are in the EEZ of Polynesia. Work on the seabed is required to determine areas of interest, with continuity favourable to exploitation. Nevertheless, there is now renewed interest in nodules and crusts due to the presence of rare metals (rare earths, molybdenum, tellurium, vanadium, zirconium, thallium…) which were not taken into account in the past. Several countries have conducted systematic analyses of their collections in order to determine the samples and areas with the highest rare metal contents.

Polymetallic nodules While the exploitation of polymetallic nodules appears possible in technical terms and hypothetical in economic terms, it remains of little relevance in national terms given the existing land-based resources.

Natural hydrogen In the current state of knowledge, exploitation of natural hydrogen cannot be considered until the very long term. This is a recent discovery on hydrothermal systems associated with mantle rock. Scientific knowledge of processes needs to be improved and flows quantified.

Appendix—2 Steering Committee

Title	First name	Surname	Position	Ministry/Organisation	Department, division…
Mrs	Ana-Paula	SEROND	Research and Development Manager	Areva	Upstream Fuel
Mr	Dominique	DELORME	President and Executive Director	La Mancha	La Mancha
Mr	Patrick	CHRISTMANN	Mineral Resources Department Manager	BRGM	
Mr	Bruno	MARTEL-JANTIN	Department Manager		Mineral Resources, Economy, Intelligence and Sustainable Development
Mrs	Nathalie	BASSALER	Department Manager	Strategic Analysis Centre	Intelligence, Foresight and International Department
Mr	Bruno	GOFFÉ	Deputy Scientific Manager	CNRS/INSU	Chair
Mr	Alain	CHEILLETZ	Professor		Centre of Petrographic and Geochemical Research
Mr	Jérôme	DYMENT	Project manager		Marine Geosciences
Mr	Abrao	CARVALHO	G3 Unit Manager	European Commission DG Industry	Steel, Non-Ferrous Metals and Mineral Ore Unit
Mr	Paul	ANCIAUX	Project Manager		
Mr	Benoît	LEGAIT	Director	*École des mines de Paris*	General Management
Mr	Damien	GOETZ	Director		Geosciences Centre
Mr	Jean-Marc	MONTEL	Director	ENSG Nancy	Management
Mr	Lev	FILIPPOV	Teacher and Researcher		
Mr	Antoine	GRECO	Director	Eramet	Industrial Affairs
Mr	J.-Jacques	REVERDY	Director		Nickel Branch
Mrs	Catherine	TISSOT-COLLE	Chairperson	Fedem	Federation of Ores, Industrial Minerals and Non-Ferrous Metals
Mr	François	BOURSE	Director of Studies	Gerpa	Foresight Methodology
Mr	Pierre	COCHONAT	Deputy Director	Ifremer	Programmes and Project Coordination Department
Mr	Jean-Luc	DEVENON	Scientific and Technological Adviser	Ifremer	Scientific and Technical Committee
Mr	Yves	FOUQUET	Project Manager	Ifremer	Fluids, Chemical Transfers and Potential Resources Project
Mr	Maurice	HERAL	Director	Ifremer	Future Planning and Scientific Strategy Department

Title	First name	Surname	Position	Ministry/Organisation	Department, division…
Mr	Denis	LACROIX	Foresight Coordinator	Ifremer	Scientific Management, Foresight Unit
Mr	Lionel	LEMOINE	Programme Manager	Ifremer	Mineral and Energy Resources Programme
Mr	Walter	ROEST	Expert in Geosciences	Ifremer	Future Planning and Scientific Strategy Department
Mr	Jean-Paul	PANCRACIO	Expert in International Maritime Law	Strategic-Research Institute of the French Military Academy	Director of Study Field 8: Legal Studies
Mr	Pascal	BARRIER	Director	LaSalle-Beauvais Institute	Management
Mr	Olivier	BAIN	Teacher and Researcher		Geology Department
Mr	Xavier	FOATA	Office Manager	Ministry of Ecology, Sustainable Development, Transport and Housing	Mineral Resources Bureau
Mrs	Alice	METAYER MATHIEU	Project Manager		
Mr	François	BERSANI	President of the Regulations and Resources Section	Ministry of Economy, Industry and Employment	General Council of Industry, Energy and Technologies
Mr	François	CLIN	Deputy Director	Ministry of Higher Education and Research	DG of Research and Innovation
Mr	Pierre	BARBEY	Terrestrial Risks Project Manager		Strategic Service for Research and Innovation
Mr	Gilles	BŒUF	Chairman	National Museum of Natural History	Chair
Mr	Jean-Yves	REYNAUD	Teacher and Researcher		Sedimentology
Mr	Vincent	CAMPREDON	Technical Adviser	Secretary of State for French Overseas Territories	Council
Mr	Pierre	MARX	Defence Adviser		
Mr	Christophe	LE VISAGE	Advisers	Secretary of State for the Sea	Council
Mr	Frederick	HERPERS			
Mr	Gilbert	TROLY	Chairman	*Société de l'industrieminérale*	Board of Governors
Mr	François	LETOURNEUX	President of IUCN France	International Union for Conservation of Nature	IUCN France
Mr	François	SIMARD	Deputy Director of Fisheries and Living Marine Resources		IUCN, Headquarters in Switzerland
Mrs	Marcia	MAIA	Deputy Director	UBO/OSU	IUEM Department
Mr	Philippe	HUCHON	Director	University of Paris 6	Earth Sciences Institute (ISTEP)

Appendix—3 Working Group

Title	First name	Surname	Position	Ministry/ Organisation	Department, division…
Mr	Dominique	DELORME	President and Executive Director	Areva La Mancha	La Mancha
Mr	Patrick	CHRISTMANN	Mineral Resources Department Manager	BRGM	Mineral Resources, Economy, Intelligence and Sustainable Development
Mr	Bruno	MARTEL-JANTIN	Department Manager		
Mrs	Nathalie	BASSALER	Department Manager	Strategic Analysis Centre	Intelligence, Foresight and International Department
Mr	Bruno	GOFFÉ	Deputy Scientific Manager	CNRS/INSU	Chair
Mr	Alain	CHEILLETZ	Professor		CRPG
Mr	Jérôme	DYMENT	Project Manager		Marine Geosciences
Mr	Jean-Marc	MONTEL	Director	ENSG Nancy	
Mr	Lev	FILIPPOV	Teacher and Researcher		Management
Mr	J.-Jacques	REVERDY	Director	Eramet	Nickel Branch
Mr	François	BOURSE	Director of Studies	Gerpa	Foresight Methodology
Mr	Pierre	COCHONAT	Deputy Director	Ifremer	Programmes and Project Coordination Department
Mr	Yves	FOUQUET	Project Manager	Ifremer	Fluids, Chemical Transfers and Potential Resources Project
Mr	Denis	LACROIX	Foresight Coordinator	Ifremer	Scientific Management, Foresight Unit
Mr	Lionel	LEMOINE	Programme Manager	Ifremer	Mineral and Energy Resources Programme
Mr	Walter	ROEST	Expert in Geosciences	Ifremer	Future Planning and Scientific Strategy Department

Title	First name	Surname	Position	Ministry/ Organisation	Department, division…
Mr	Jean-Paul	PANCRACIO	Expert in International Maritime Law	Strategic-Research Institute of the French Military Academy	Director of Study Field 8: Legal Studies
Mr	Pascal	BARRIER	Director	LaSalle-Beauvais Institute	Management
Mr	Olivier	BAIN	Teacher and Researcher		Geology Department
Mr	Xavier	FOATTA	Office Manager	Ministry of Ecology, Sustainable Development, Transport and Housing	
Mrs	Alice	METAYER-MATHIEU	Project Manager		Mineral Resources Bureau
Mr	François	BERSANI	President of the Regulations and Resources Section	Ministry of Economy, Industry and Employment	General Council of Industry, Energy and Technologies
Mr	François	CLIN	Deputy Director	Ministry of Higher Education and Research	DG of Research and Innovation
Mr	Pierre	BARBEY	Terrestrial Risks Project Manager		Strategic Service for Research and Innovation
Mr	François	LETOURNEUX	President of IUCN France	International Union for Conservation of Nature	IUCN France
Mr	François	SIMARD	Deputy Director of Fisheries and Living Marine Resources		IUCN, Headquarters in Switzerland
Mrs	Marcia	MAIA	Deputy Director	UBO/OSU	IUEM Department

Appendix—4 Experts Consulted

Title	First name	Surname	Position	Ministry/Organisation	Department, division…
Mr	Christian	HOCQUARD	Researcher	BRGM	Mineral Resources
Mr	Fabrice	BRUNET	Researcher	CNRS/INSU	Hydrogen Department
Mr	Iain	SHEPHERD	DG Industry	European Commission	Strategic Mineral Resources
Mrs	Claire	NOUVIAN	Expert	Consultant	Biodiversity and Deep-Sea Environment
Mr	Philippe	MASCLET	Office manager	Defence Procurement Agency	Research and Innovation; Materials and Chemistry
Mr	Alain	TATOUT	Expert		
Mrs	Elisabeth	GIBERT-BRUNET	Expert		

Title	First name	Surname	Position	Ministry/Organisation	Department, division…
Mrs	Joëlle	GALÉRON	Project manager	Ifremer	Project: Biodiversity and Functioning of Deep-Sea Ecosystems
Mr	Jean-Luc	CHARLOU	Researcher	Ifremer	Fluids, Chemical Transfers and Potential Resources; Geochemistry, Metallogeny
Mrs	Odile	GAUTHIER	Director	Ministry of Ecology, Sustainable Development, Transport and Housing	Department of Water and Biodiversity
Mrs	Véronique	PERRIER	Expert		
Mr	Charles	LAMIRAUX	Expert		Marine Environment
Mr	Élie	JARMACHE	Expert Adviser	General Secretariat for the Sea	Legal Department
Mr	Philippe	ESPINASSE	Director	Technip	Submarine Mineral Extraction Technologies

Appendix—5 Advantages and Constraints of the Main Deep-Sea Minerals

	Critical metal Europe 2030	Critical metal United States	Type of ocean mineral deposit	Concentrations and supply
Gallium	Yes	Yes	Hydrothermal sulphides	China, Germany, Kazakhstan, Ukraine
Germanium	Yes	No	Hydrothermal sulphides	China (67 %), Russia (4 %), US (4 %)
Indium	Yes	Yes	Hydrothermal sulphides	China (52 %), Korea (14 %)
Antimony	Yes	No	Hydrothermal sulphides	China (89 %)
PGMs Ru, Rh, Pd, Re, Os, Ir, Pt	Yes	Yes Rh, Pt, Pd	Crusts	South Africa and Russia (90 %)
Magnesium	Yes	No	Hydrothermal sites in the mantle	China (56 %)
Graphite	Yes	No	–	China (73 %), India (12 %)
Tantalum	Yes	Yes	–	Brazil (26 %), Mozambique (16 %), Rwanda (15 %)
Beryllium	Yes	No	–	United States (89 %), China (10 %)
Fluorine	Yes	No	–	China (56 %), Mexico (18 %)

	Critical metal Europe 2030	Critical metal United States	Type of ocean mineral deposit	Concentrations and supply
Niobium	Yes	Yes	Nodules—crusts	Brazil (92 %)
Rare earths La, Ce, Pr, Nd,Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu	Yes	Yes	Nodules—crusts	China (99 %)
Yttrium	Yes	Yes	–	China (99 %)
Tungsten	Yes	No	Nodules	China (85 %)
Silver	No	No	Hydrothermal sulphides	Peru (18 %), Mexico (16 %), China (13 %)
Cobalt	No	No	Crusts and sulphides	Congo (51 %), Zambia (12 %)
Zinc	No	No	Hydrothermal sulphides	China (30 %), Peru (13 %), Australia (12 %)
Copper	No	Yes	Sulphides, nodules, crusts	Chila (34 %), Peru (8 %), China (7 %), United States (7 %)
Nickel	No	No	Nodules—crusts	Russia (17 %), Indonesia (15 %), Philippines (10 %), New Caledonia (9 %)
Gold	No	No	Hydrothermal sulphides	China (14 %), Australia (10 %), US (9 %)
Titanium	No	Yes	Nodules—crusts	South Africa (19 %), Australia (18 %), China (10 %)
Manganese	No	Yes	Nodules—low T° hydrothermal crusts	China (21 %), Australia (18 %), South Africa (17 %), Gabon (11 %)
Thallium	No	Yes	Nodules—crusts	Canada, Europe, US
Vanadium	No	Yes	Nodules—crusts	China (41 %), South Africa (32 %), Russia (25 %)
Lithium	No	Yes	No	Chile (35 %), Australia (34 %), China (18 %)
Tellurium	No	Yes	Hydrothermal sulphides	Japan, Russia, Peru, Canada
Selenium	No	No	Hydrothermal sulphides	Germany (30 %), Belgium (9 %), Canada (8 %)

	Annual production Source: USGS	Tension indicator Europe 2030	Recyclability	Substitutability	Reserves
Gallium	106 t (2010)	4	Yes	Yes for certain applications	?
Germanium	120 t (2010)	2.2	Yes (30 %)	Undocumented	?
Indium	574 t (2010)	3.3	Low	Yes for certain applications	?
Antimony	135,000 t (2010)	0.01	Low	Low	1,800,000 t
PGMs Ru, Rh, Pd, Re, Os, Ir, Pt	Pt: 178 t (2009) Pd: 195 t (2009)	1.3	Yes (60 t in 2009)	Yes between PGMs	71,000 t
Magnesium	5 Mt (2009)	–	Limited	Undocumented	2,300 Mt
Graphite	1.1 Mt (2010)	–	Possible		71 Mt
Tantalum	670 t (2010)	1	Low	Potential	110,000 t
Beryllium	190 t (2010)	–	Low	Low	?
Fluorine	5.4 Mt	–	Low	Low	230 Mt
Niobium	63,000 t (2010)	0.03	Yes (20 %)		2.9 Mt
Rare earths La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu	130,000 t (2010)	1.7	Low	Yes but decreased performance	110 Mt
Yttrium	8900 t (2010)		Low	Low	540,000 t
Tungsten	61,000 t (2010)	1	Yes	Low	2.9 Mt
Silver	22,200 t (2010)	0.8	Yes (1600 t in 2010)	Yes	510,000 t
Cobalt	88,000 t (2010)	0.4	Yes (24 % in 2010)	Limited	7.3 Mt
Zinc	12 Mt (2010)	-	Yes	Yes	250 Mt
Copper	16.2 Mt (2010)	0.2	Yes	Yes	630 Mt
Nickel	1.5 Mt (2010) land-based reserves 76 Mt	–	Yes	Moderate	76 Mt
Gold	2500 t (2010)	–	Yes	Yes	51,000 t
Titanium	6.3 Mt (2010)	0.3	No	No	690 Mt
Manganese	13 Mt (2010)	–	Low	No	630 Mt
Thallium	10 t (2010)	–	No	Low	380 t
Vanadium	56,000 t (2010)	–	Low	Yes	13.6 Mt
Lithium	25,300 t (2010)	–	Low	Yes	13 Mt
Tellurium	unavailable >125 t (2010)	–	No	Yes	22,000 t
Selenium	2260 t (2010)	–	No	Yes	88,000 t

NB: several critical elements are directly related to concentrations of base metals such as copper and zinc.

Bibliography

Deep-Sea Environment

Bouchet, P. (2006). The magnitude of marine biodiversity. In M. D. Carlos (ed.), *The exploration of marine biodiversity, scientific and technological challenges* (pp. 31–64).

Desbruyères, D. (2010). *Les trésors des abysses*. Éditions Quæ, collectionCarnets de sciences, p. 184. Glover A. G., Smith C. R., 2003. The deep-sea floor ecosystem: Current status and prospects of anthropogenic change by the year 2025. *Environmental Conservation, 300*(3), 219–241.

Mahatma, R. (2009). *Meiofauna Communities of the Pacific Nodule Province: abundance, diversity and community structure*. Universität Oldenburg. PhD Thesis.

Miljutin, D. M., Miljutina, M., Martinez Arbizu, P., & Galéron, J. (2011). Deep-sea nematode assemblage has not recovered 26 years after experimental mining of polymetallic nodules (Clarion-Clipperton fracture zone, tropical Eastern Pacific). *Deep-Sea Research I, 58,* 885–897.

Miljutina, M., Miljutin, D., Mahatma, R., & Galéron, J., 2010. Deep-sea nematodeassemblagesof theClarion-Clipperton nodule province (tropical north-eastern Pacific). *Marine Biodiversity, 40,* 1–15.

Mullineaux, L. S. (1987). Organisms living on manganese nodules and crusts: Distribution and abundance at three North Pacific sites. *Deep-Sea Research, 34,* 165–184.

Rex, M. A., EtterR. J., Morris, J. S., Crouse, J., McClainC. R., Johnson, N. A., Stuart, C. T., DemingJ. W., Thies, R., & Avery, R. (2006). Global bathymetric patterns of standing stock and body size in the deepsea benthos. *Marine Ecology Progress Series, 317,* 1–8.

Smith, C. R., Levin, L. A., Koslow, A., Tyler, P. A., Glover, A. (2008). The near future of deep seafloor ecoystems. In N. Polunin (ed.), *Aquatic ecosystems: Trends and global prospects* (pp. 334–351). Cambridge University Press.

Veillette, J., Sarrazin, J., Gooday, A. J., Galéron, J., Caprais, J. C., Vangriesheim, A., Etoubleau, J., Christian, J. R., & Juniper, K. (2007). Ferromanganese nodule fauna in the tropical North Pacific Ocean: Species richness, faunal cover and spatial distribution. *Deep-Sea Research I, 54,* 1912–1935.

Characteristics and Formation Process of Potential Deep-Sea Mineral Resources

Cronan, D. (2000). *Handbook of marine mineral deposits* (p. 406). CRC Press London.

Fouquet, Y. (2002). Sulfures polymétalliques hydrothermaux océaniques. *Les Techniques de l'Industrie Minérale, 15,* 51–65.

Fouquet, Y. (2003). Prospective sur les ressources minérales des grands fonds océaniques, état des connaissances, éléments d'appréciation. Ifremer, rapport interne DRO/GM/03/10 6, p. 57.

Y. Fouquet, D. Lacroix (eds.), *Deep Marine Mineral Resources*,
DOI 10.1007/978-94-017-8563-1, © Éditions Quæ 2014

Fouquet, Y., Cambon, P., Etoubleau, J., Charlou, J.-L., Ondréas, H., Barriga, F., Cherkashov, G., Semkova, T., Poroshina, I., Bohn, M., Donval, J.-P., Henry, K., Murphy, P., & Rouxel, O. (2010). Geodiversityof hydrothermal processalong the Mid-Atlantic Ridge and ultramafic-hosted mineralization: a new type of oceanic Cu-Zn-Co-Au volcanogenicmassive sulphide deposit. In P. Rona, C. Devey, J. Dyment, & B. Murton (eds.), *Diversity of hydrothermal systems on slow spreading ocean ridges* (pp. 321–367) edited by AGU Geophysical Monograph Series, 188.

Hein, J., Koschinsky, A., Bau, M., Manhein, F., Kang, J. K., & Robert, L. (2000) Cobalt-Rich Ferromanganese Crust in the Pacific. In D. Cronan (ed.), *Handbook of marine mineral deposits* (pp. 239–279). CRC Press London.

Hoffert, M., 2008. *Les nodules polymétalliques dans les grands fonds océaniques* (p. 429). Société géologique de France, Éditions Vuibert.

Lenoble, J.-P. (1996). Les nodules polymétalliques, bilan de 30 ans de travaux dans le monde. *Chronique de la Recherche Minière, 524,* 15–37.

Rona, P. (2003). Resources of the seafloor. *Science, 299,* 673–674.

Scott, S. D. (2001). Deep Ocean mining. *Geoscience Canada, 28*(2), 87–94.

Scientific Knowledge and Challenges Related to Hydrogen

Cannat, M., Fontaine, F., & Escartin, J. (2010). Serpentinizationand associated hydrogen and methane fluxes at slow-spreading Ridges. In P. Rona, C. Devey, J. Dyment, & B. Murton (eds.), *Diversity of hydrothermal systems on slow-spreading ocean ridges* (pp. 241–264).

Charlou, J.-L., Bougault, H., Appriou, P., Nelsen, T., & Rona, P. (1991). Different TDM/CH_4 hydrothermal plume signatures: TAG site at 26° N and serpentinized ultrabasic diapir at 15° 05' N on the Mid-Atlantic Ridge. *Geochimica Cosmochimica Acta, 55*(11), 3209–3222.

Charlou, J.-L., & Donval, J.-P. (1993). Hydrothermal methane venting between 12° N and 26° N along the Mid-Atlantic Ridge. *Journal of Geophysical Research, 98*(B6), 9625–9642.

Charlou, J.-L., Fouquet, Y., Bougault, H., Donval, J.-P., Etoubleau, J., Jean-Baptiste, P., Dapoigny, A., Appriou, P., & Rona, P. A. (1998). Intense CH_4 plumes generated by serpentinization of ultramafic rocks at the intersection of the 15° 20' N Fracture Zone and the Mid-Atlantic Ridge. *Geochimica Cosmochimica Acta, 62*(13), 2323–2333.

Charlou, J.L., Donval, J.-P., Douville, E., Jean-Baptiste, P., Radford-Knoery, J., Fouquet, J., Dapoigny, A., & Stievenard, M. (2000). Compared geochemical signatures and the evolution of Menez Gwen (37° 50' N) and Lucky Strike (37° 17' N) hydrothermal fluids, south of the Azores Triple Junction on the Mid-Atlantic Ridge. *Chemical Geology, 171,* 49–75.

Charlou, J. L., Donval, J.-P., Fouquet, Y., Jean-Baptiste, P., & Holm, N. G. (2002). Geochemistry of high H_2 and CH_4 vent fluids issuing from ultramafic rocks at the Rainbow hydrothermal field (36° 14' N, MAR). *Chemical Geology, 191,* 345–359.

Charlou, J.-L., Donval, J.-P., Ondreas, H., Fouquet, Y., Jean-Baptiste, P., & Fourré, E. (2010). High production and fluxes of H_2 and CH_4 and evidence of abiotic hydrocarbon synthesis by serpentinization in ultramafic-hosted hydrothermal systems on the Mid-Atlantic Ridge. In P. Rona, C. Devey, J. Dyment, & B. Murton (eds.), *Diversity of hydrothermal systems on Slow-Spreading Ocean Ridges* (pp. 265–296).

Emmanuel, S., & AgueJ. J. (2007). Implications of present-day abiogenic methane fluxes for the early Archean atmosphere. *Geophysical Research Letters, 34,* L-15810.

Holloway, J. R., & O'Day, P. A. (2000). Production of CO_2 and H_2 by diking-eruptive events at mid-ocean ridges: Implications for abiotic synthesis and global geochemical cycling. *International Geology Review, 42,* 673–683.

Holm, N. G., & Charlou, J.-L. 2001. Initial indications of abiotic formation of hydrocarbons in the Rainbow ultramafic hydrothermal system, Mid-Atlantic Ridge. *Earth Planetary Science Letters, 191,* 1–8.

Horita, J., & Berndt, M. E. (1999). Abiogenic methane formation and isotopic fractionation under hydrothermal conditions. *Science, 285,* 1055–1057.

Keir, R. S. (2010). A note on the fluxes of abiognic methane and hydrogen from mid-ocean ridges. *Geophysical Research Letters, 37,* L24609 doi:10.1029/2010GL045362.

Konn, C., Charlou, J.-L., Donval, J.-P., Holm, N. G., Dehairs, F., & Bouillon, S. (2009). Hydrocarbons and oxidized organic compounds in hydrothermal fluids from Rainbow and Lost City ultramafic-hosted vents. *Chemical Geology, 258,* 299–314.

Konn, C., Testemale, D., Querellou, J., Holm, N. G., & Charlou, J. L. (2011). New insight into the contributions of thermogenic processes and biogenic sources to the generation of organic compounds in hydrothermal fluids. *Geobiology, 9,* 79–93.

McCollom, T. M., & Seewald, J. S. (2001). A reassessment of the potential for reduction of dissolved CO_2 to hydrocarbons during serpentinization of olivine. *Geochimica Cosmochimica Acta, 65,* 3769–3778.

McCollom, T. M., & Seewald, J. S. (2007). Abiotic synthesis of organic compounds in Deep-Sea hydrothermal environments. *Chemical Review, 107,* 382–401.

Mevel, C. (2003). Serpentinization of abyssal peridotites at mid-ocean ridges. *Comptes rendus de Géosciences, 335,* 825–852.

Marcaillou, C. (2011). Serpentinisationet production d’hydrogène en contexte de dorsale lente: approche expérimentale et numérique. Thèse, janvier 2011, université de Grenoble.

Marcaillou, C., Munoz, M., Vidal, O., Parra, T., & Harfourche, M. (2011). Mineralogical evidence for H_2 degassing during serpentinization at 300 °C/300 bar. *Earth Planetary Science Letters, 303,* 281–290.

Training Organisations and Establishments in France and Europe

Anonymous. (2007). Géologie minière, *Géologues*, numéro spécial, 152.

Association franco-allemandepour la science et la technologie. (2010). Approvisionnementde l’Europe en matières premières minérales non-énergétiques, métaux et minéraux industriels, 3–4 juin 2010, 110 rue de Grenelle, 75357 Paris.

CNRS–INSU. (2011). Prospectivede l’Institut national des sciences de l’univers, Sciences de la Terre, mars 2011.

European, U. (2008). The raw materials initiative—meeting our critical needs from growth and jobs in Europe. Communication from the Commission to the European Parliament and the Council, COM, 699.

Varet, J. (2009). *Emploi et formation en géosciences*. État des lieux des formations universitaires en France. Proposition de création d’une école BRGM. Rapport final BRGM/RP-57587-FR. 70.

Foresight Approach and Methods

Cornish, E. (2004). *Futuring: The exploration of the future*. Bethesda; Md. World Future Society, p. 313. Glenn J. C., Gordon T. J. 2010. Futures research methodology (CD-ROM). New York: American Councilfor the United Nations University.

Godet, M. (2007). *Manuel de prospective stratégique*. Tome 1: une indiscipline intellectuelle, tome2: l’art et la méthode, Dunod 3e Édition.

Jantsch, E. (1967). *La prévision technologique: cadre, techniques et organisation*. OCDE.

de Jouvenel, H. (2004). *Invitation à la prospective*. Futuribles, collection Perspectives.

Lempert, R., Popper, J., & Bankes, S., (2003). *Shaping the next one hundred years: New methods for quantitative, long-term policy analysis*. Santa Monica (California): Rand Corporation.

Mermet, L. (Dir.). (2005). Étudier les écologies futures: un chantier ouvert pour les recherches prospectives environnementales. Editions PIE Peter Lang. *Ecopolis* N °5. p. 409.

Micic, P. (2006). *Das ZukunftsRadar. Die wichtigsten Trends, Technologien und Themenfür die Zukunft*. Offenbach: Gabal management.

Schwartz, P. (1991). *The art of the long view*. London: Doubleday Currency.

Slaughter, R. (ed.). (1996). *The knowledge base of future studies* (p. 419). Victoria: DDM Media Group. T. 1: *Organisations, Practices, Products*. T. 2: *Direction & Outlooks*. T.3: *Foundations.*

Van der Heijden, K. (1996). *Scenarios, the art of strategic conversation* (p. 299). Chichester: Wiley.

Van Notten, P. (2005). *Writing on the wall. Scenario development in times of discontinuity*. Florida(Massachusetts): Phd Dissertation.

National and International Foresight Studies (2025, 2030, 2050 world visions)

Boniface, P. (Dir.). 2010. Quel monde en 2030? La Revue internationale et stratégique, 80. http://www.iris-france.org/Archives/revue/revue_internationale_strategique.php3.

European, C. (2009). The World in 2025. http://ec.europa.eu/research/social-sciences/pdf/the-world-in-2025-report_en.pdf.

Hammond, R. (2008). The World in 2030. http://www.hammond.co.uk/The%20World%20In%202030%20Ray%20Hammond.pdfhttp://www.rayhammond.com/Le%20Monde%202030.pdf [in French].

HSBC. (2011). The World in 2050. http://www.research.hsbc.com/midas/Res/RDV?ao=20&key=ej73gSSJVj&n=282364.PDF.

PricewaterhouseCooper. (2011). The World in 2050. http://www.pwc.com/en_GX/gx/world-2050/pdf/world-in-2050-jan-2011.pdf.

Tenzer, N. (2011). Le monde à l’horizon 2030: la règle et le désordre. Éditions Perrin. http://www.editions-perrin.fr/fiche.php?F_ean13=9782262026684.

The National Intelligence Council. (2008). Global trends 2025. http://www.dni.gov/nic/PDF_2025/2025_Global_Trends_Final_Report.pdf.

Associate Partners

AREVA
brgm
Centre d'analyse stratégique
CNRS INSU

MINES ParisTech
GÉOLOGIE

ERAMET
Fedem
GERPA
IRSEM
LaSalle

Technip
UICN
UBO
UPMC

Y. Fouquet, D. Lacroix (eds.), *Deep Marine Mineral Resources*,
DOI 10.1007/978-94-017-8563-1, © Éditions Quæ 2014

Text revision and project coordination
Nelly Courtay
Editing
Hélène Berre
Cover and formatting
Carine Vadet-Perrot/ Graine de papier
Graphics (Figs. 1, 2, 3, 5, 6, 7, 8, 9 and tables in Appendix 6)
Bluelife, 34000 Montpellier