Chapter 1
Study Summary

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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

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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;

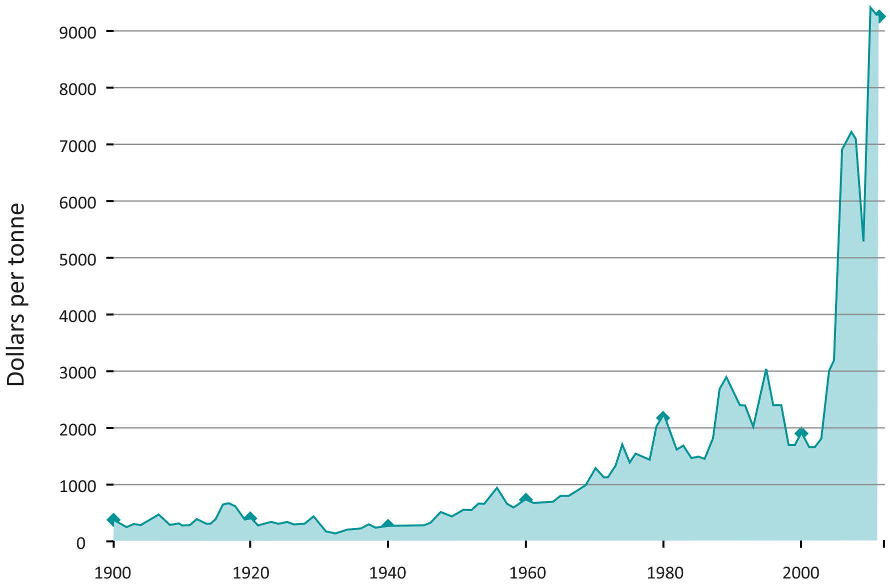

Fig. 1.1 Evolution of copper prices during the twentieth century. (Source: United States Geological Survey)

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.

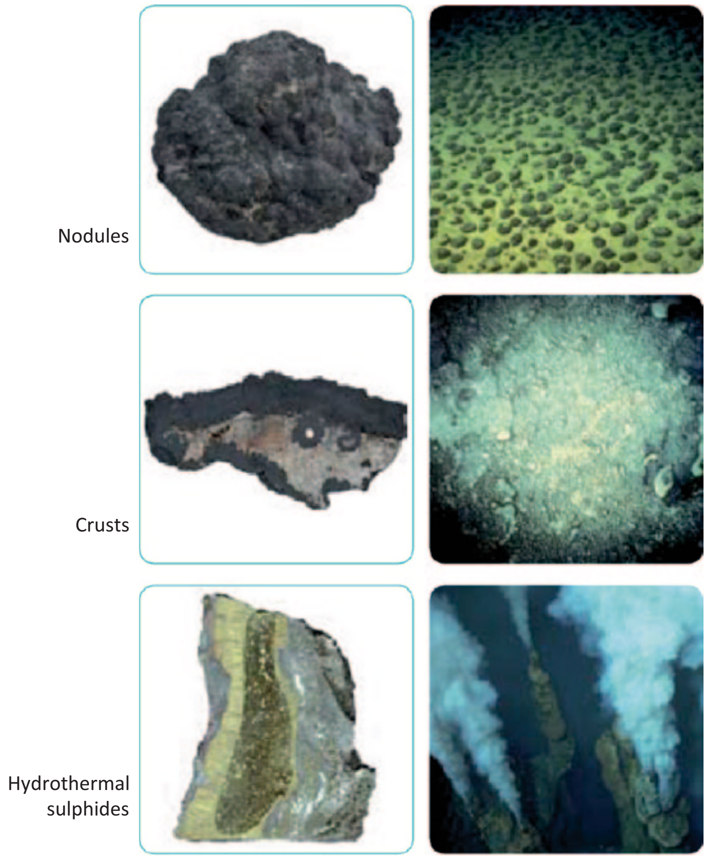

Fig. 1.2 Types of deep-sea mineral deposits

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).

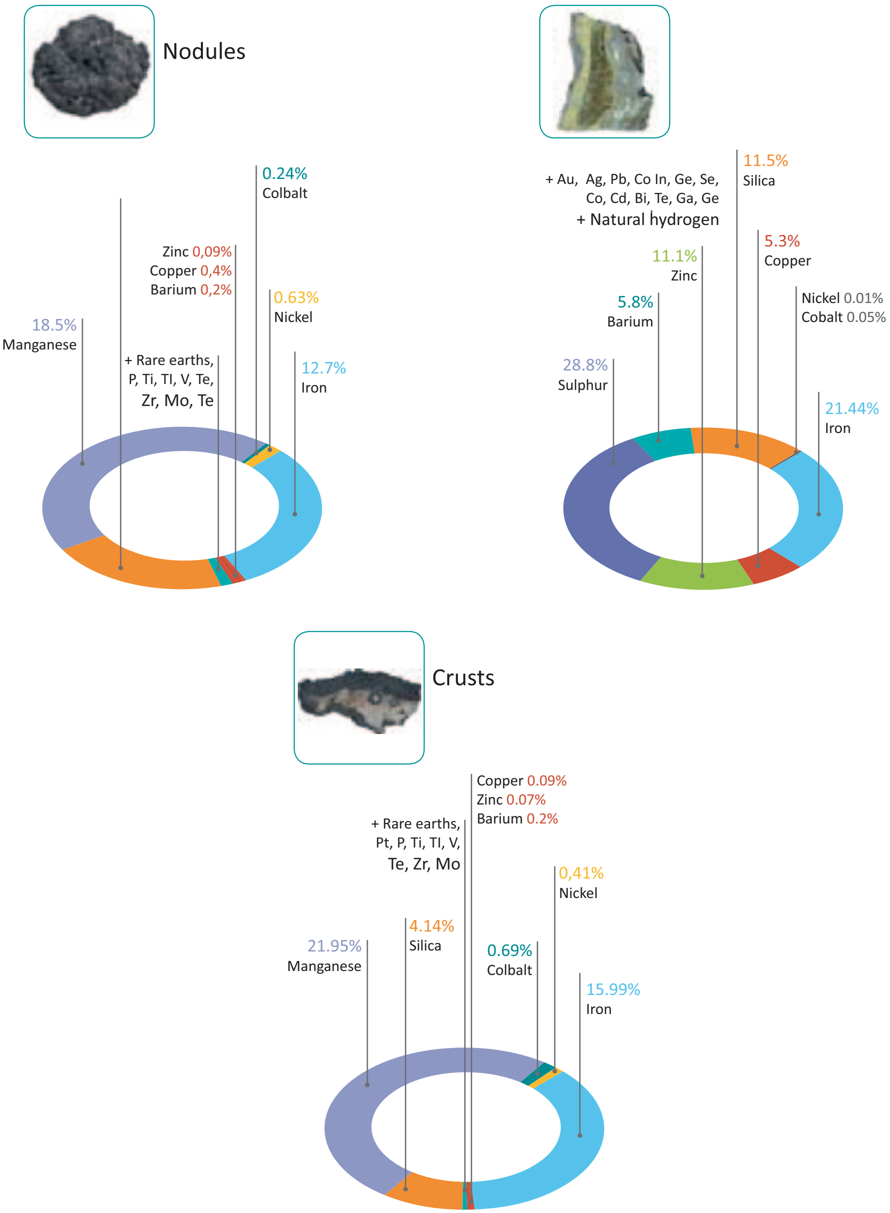

Fig. 1.3 Concentrations (% weight) of major elements in deep-water mineral deposits

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

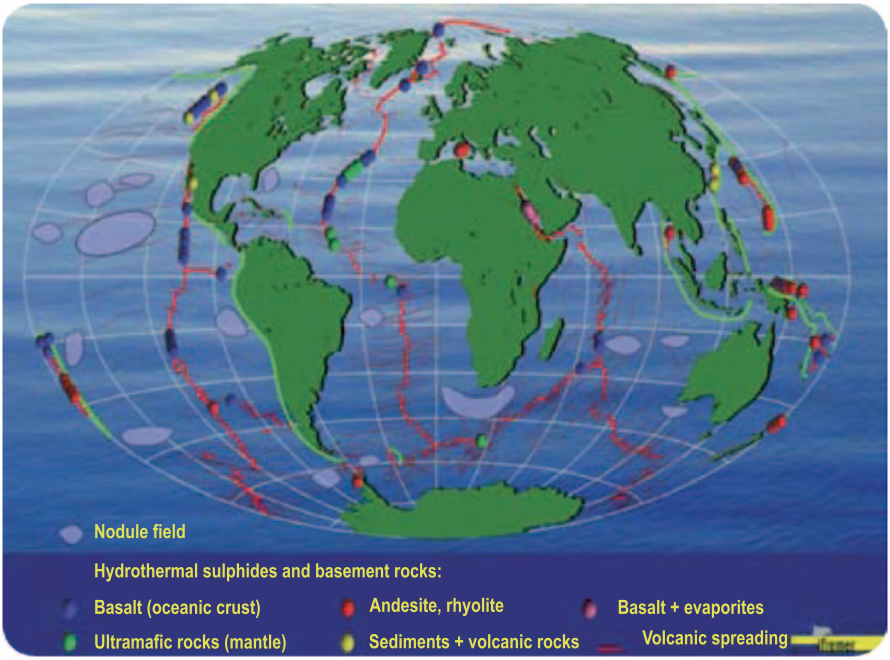

Fig. 1.4 Location of hydrothermal sites and nodule fields around the globe

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.

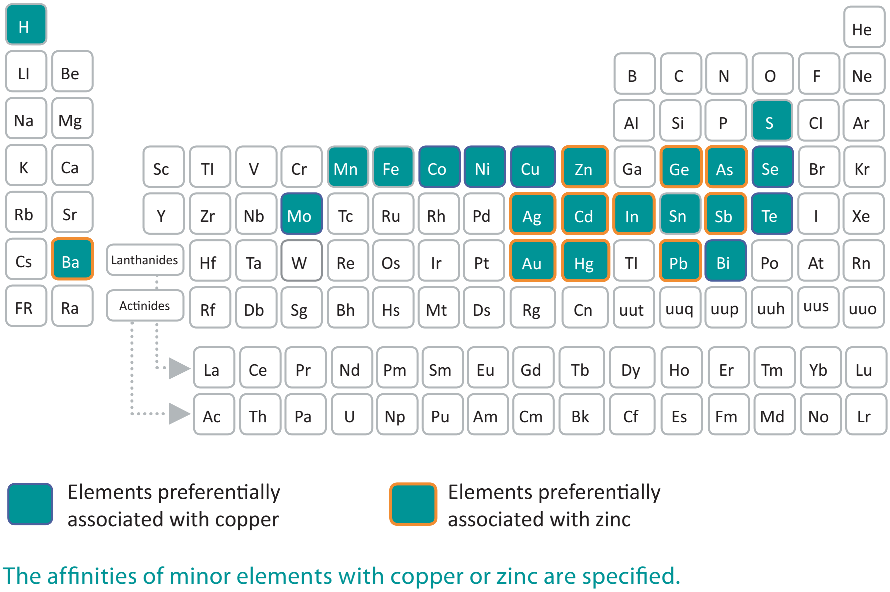

Fig. 1.5 Metals present in hydrothermal sulphide deposits

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,

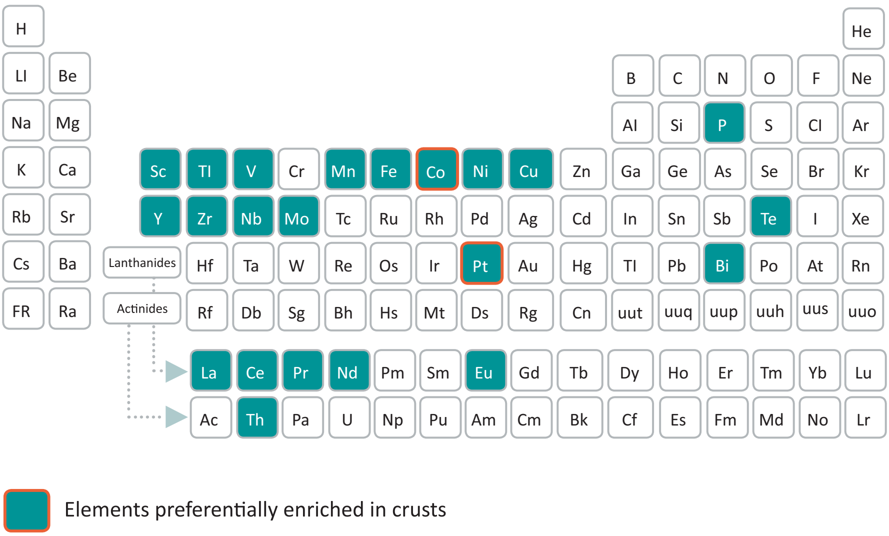

Fig. 1.6 Elements accumulated in nodules and hydrogenetic crusts

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.

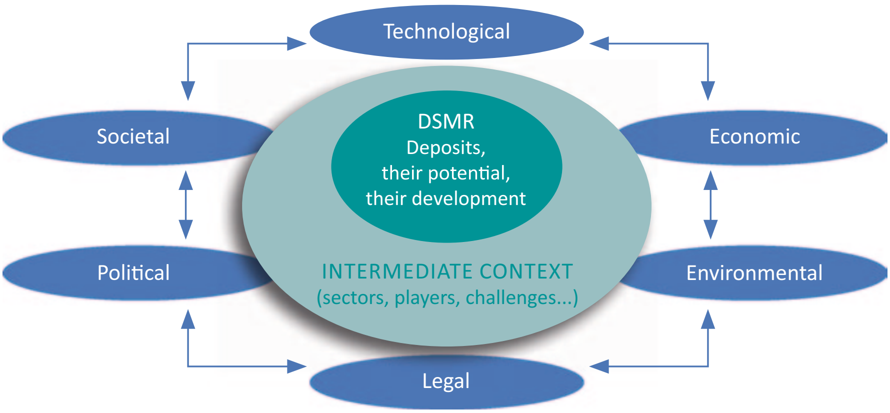

Fig. 1.7 Aspects analysed in the study of variables relating to deep-sea mineral resources. (Source: Gerpa)

- 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.

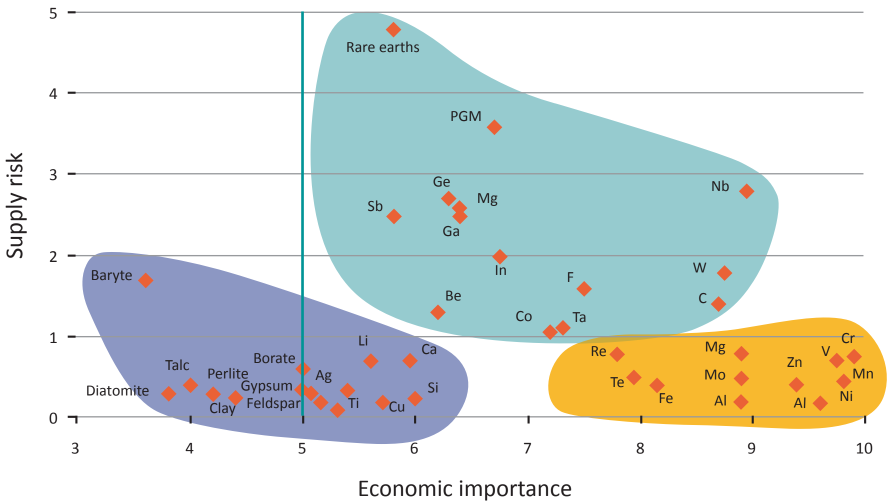

Fig. 1.8 European vision of the position of metals according to their economic importance and supply risks. (Source: European Union 2010)

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”.

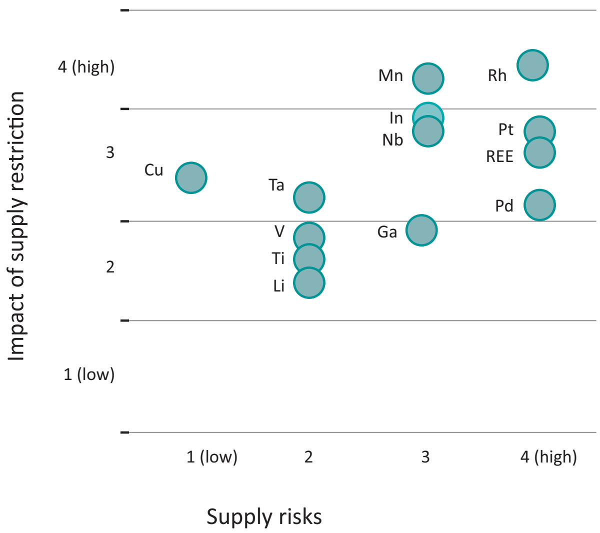

Fig. 1.9 North-American vision of the position of metals according to supply risks and the impact of a restriction. (Source: United States Geological Association (USGA) 2009)

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.

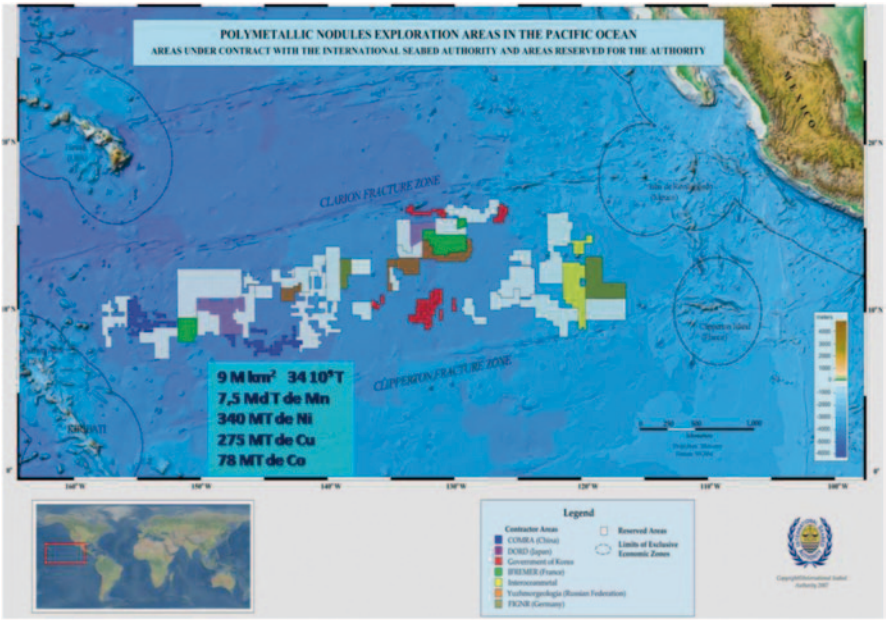

Fig. 1.10 Position of "nodule" contracts in the Clarion-Clipperton Zone

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.