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Technological Trends in Ocean Mining

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Technological trends in ocean mining

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The ocean and, in particular, the deep-sea floor offer vast potentials of various minerals: polymetallic nodules, metalliferous sediments of hydrothermal origin, phosphorites, uraniferous mud and mineral sands, as well as oil and gas. It is now established that the manganese nodules of the North Pacific may exceed in nickel, copper and cobalt content all known reserves on land. Covered by several kilometres of water column and in what was once considered a hostile or even deadly environment, they can be turned into resources only with the aid of new techniques and technologies for exploration, mining and processing.

Recent developments in acoustics, electronics and materials lead to new exploration equipment and strategies to locate and quantify the minerals on or below the deep ocean floor. Advances in hydraulics and offshore technology indicate ways to mine the ores, and recent results in mineral processing and metallurgy allow one to produce and refine the metals. These technical trends and results occur in certain, most important, settings: ocean space is no longer regarded as a hostile barrier but with ever-increasing awareness as an environment to be thoroughly protected; political trends as evolving from the Third U.N. Law of the Sea Conference influence the technology and are influenced by it; market factors, such as the future demand for nickel, have an important impact. And, above all, mineral recovery is an exercise to satisfy the human mind, curious and adventurous and concerned with this globe's further wellbeing.

1. Introduction: opportunities for mineral supply from the deep ocean floor

1.1. *An international régime for the high sea*

The eleventh session of the Third U.N. Law of the Sea Conference has just started in New York. The Conference first convened almost 10 years ago in Caracas. Since then, many meetings in Geneva and New York have kept thousands of experts busy, have required many millions of dollars in expenses and have left thousands of millions of pages of text written and copied. Despite surprisingly quick agreements on such important issues as passage through straits, or the distribution of large seabed areas with vast potential for oil and gas to coastal states, the conference came to a halt, last year, over something less important. Dispute arose right from the beginning of the Conference but could not be settled over metal-rich nodular concretions on the ocean floor, at great water depth and far beyond the technical and legal reach of men. The imagination of delegates and the public, especially in the Third World, was excited by careless reports on easily recoverable riches in the ocean depths. These last resources of the globe were to be protected from the profit hunger of individual capitalists. Complex administrative rules and regulations for the use of ocean minerals were designed eventually to channel the expected enormous wealth from ocean mining to all mankind.

The story might have ended with a twentieth-century version of La Fontaine's fable of the hidden treasure. The father would have told his sons not to dig and work for the treasure in the soil and thus make the soil rich and fertile. Rather, the father would have told his sons to first set up an administration for the treasure and to establish rules and regulations for the work. This being a truly difficult task, work has never started....

The stalemate of the Law of the Sea Conference resulted in initiatives from some countries to negotiate reciprocal bilateral agreements with intermediate rules pending ultimate agreement and the eventual realization of an international régime. Regardless of whether the Law of the Sea Conference regains momentum and obtains results or whether the bilateral solutions prevail for the next decades anybody with a sense of responsibility and realism should thoroughly evaluate the potential of ocean-floor minerals and the technical, economic and ecological problems associated with their exploitation. Are they worth all this political effort to constitute a model field for a future New Economic Order with more social justice and democratic participation and, last but not least, sufficient efficiency to generate welfare for all mankind? Could ocean mining and its rules and regulations as initiated at the end of the twentieth century become a model case for further, even more ambitious concepts of the world community, such as the utilization of the Moon and the Moon Treaty?

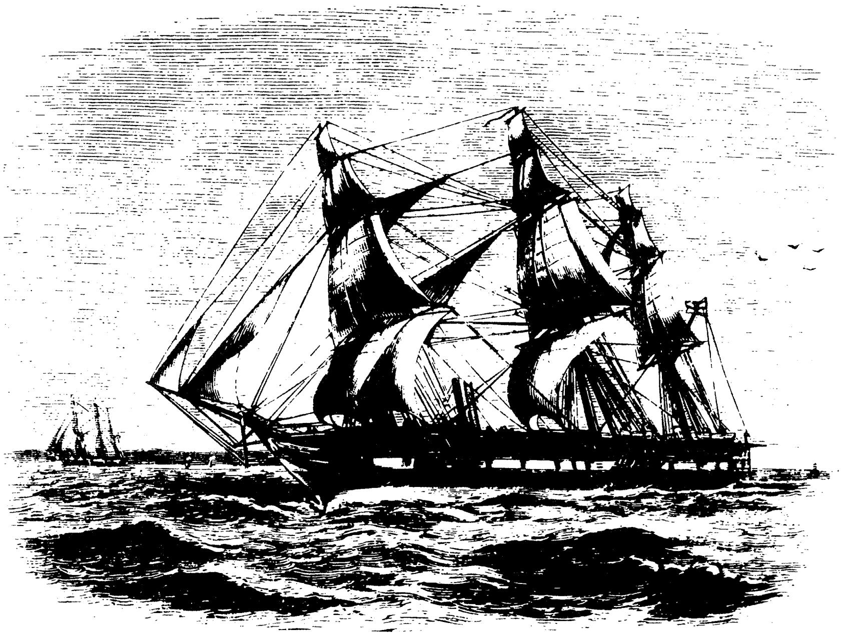

FIGURE 1. H.M.S. *Challenger*.

1.2. *Nature and resource potential of sea-floor minerals*

Polymetallic nodular sea-floor concretions have been explored and their exploitation tested during the 1970s after having been known as a geological curiosity since the first scientific ocean research with H.M.S. *Challenger* in the 1870s (figure 1). Exploration and some engineering research on mining and smelting performed by companies in various countries proved their economic potential as a future source for nickel, cobalt, copper, manganese and other metals provided that a number of sizeable economic and technical problems connected with exploration and mining could be satisfactorily overcome. After more than 10 years of exploration there is now sufficient evidence to suppose that the nodules contain more nickel and cobalt and probably almost as much manganese as all known metal deposits on land. They are distributed, however, on vast spaces of soft sediment and they cover millions of square kilometres at great water depths of 4000–6000 m, mostly in the Pacific Ocean (figure 2).

The morphology of the sea floor is mountainous with crevasses, escarpments and troughs rather than wide, undulating plains as the optimists had thought. The coverage of the sea floor with nodules, and their shape and metal content, vary considerably, even over short distances. Exploration of economic nodule deposits and their collection and exploitation will therefore require new technologies to be applied under totally adverse environmental conditions: the open ocean, thousands of miles from land bases, smelters and markets. The complex mineralogical character of sea-floor nodules and their character as a bulk ore will require novel metallurgical processes to extract and separate the metals. The scale of these problems is comparable with that of heavy oil or tar sand exploitation. But the economics of metal production are much more acute than in the artificially elevated markets of hydrocarbons.

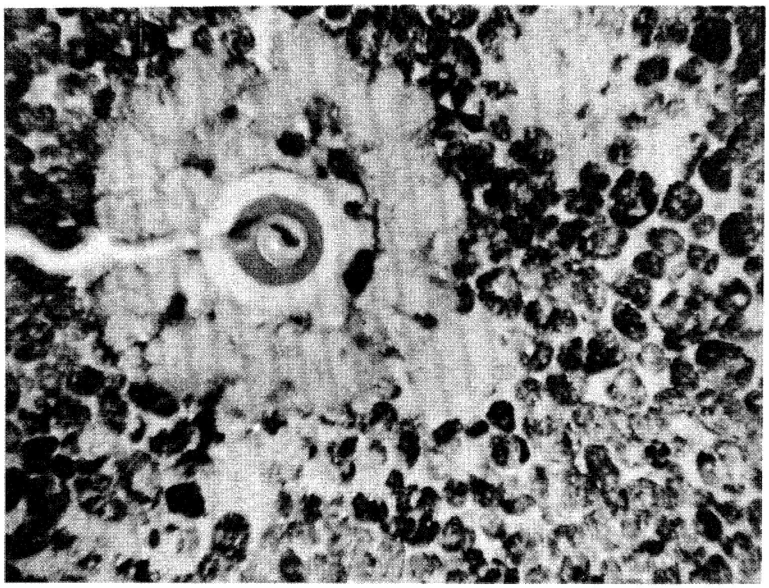

FIGURE 2. Polymetallic nodules on the Pacific sea floor.

What was said for the nodules holds to some extent for metal sulphides on the ocean floor. The project ‘Atlantis II Deep’ in the Red Sea (figure 3), involving fairly large amounts of heavy metal sulphides, is considered as a pioneer project and a model case for responsible development in ocean mining and will be discussed in more detail. Since metal sulphides have recently been found at other locations on the bottom of the open ocean, the economic potential of this type of ore has increased. It may remain, however, below the potential of the polymetallic nodules.

Last but not least, phosphorite concretions occurring in medium water depths of 400–500 m should be mentioned. They may attain considerable local significance for the supply of phosphates, as in the agricultural economy of New Zealand. Phosphorites occur off its coasts, on the Chatham Rise, east of South Island (figure 4).

Other ocean minerals such as low concentrations of uranium in organic oozes, or industrial minerals and tin in offshore placer deposits, should be added to the list of ocean floor minerals.

They occur in shallow waters and do not offer the same scope for resource potential nor the same technological, economic, political or legal problems as the deep-sea minerals. We should remember, however, that tin dredging started almost 100 years ago in southeast Asian waters and it is thus the oldest example of offshore mining.

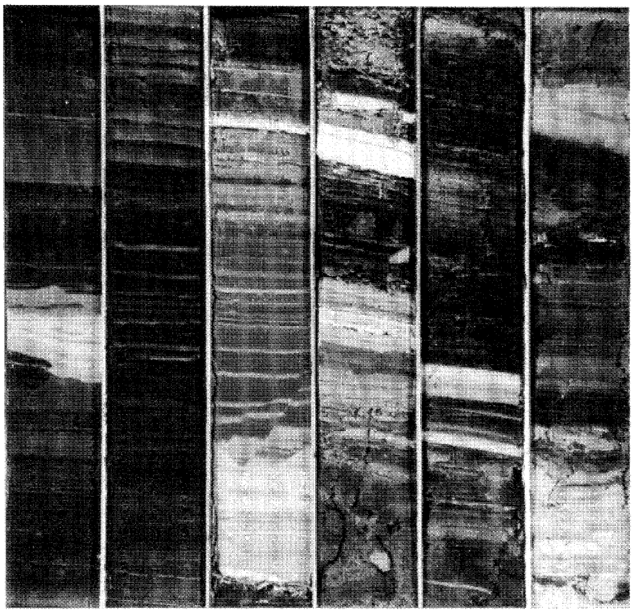

Figure 3. Metal sulphides in the Red Sea.

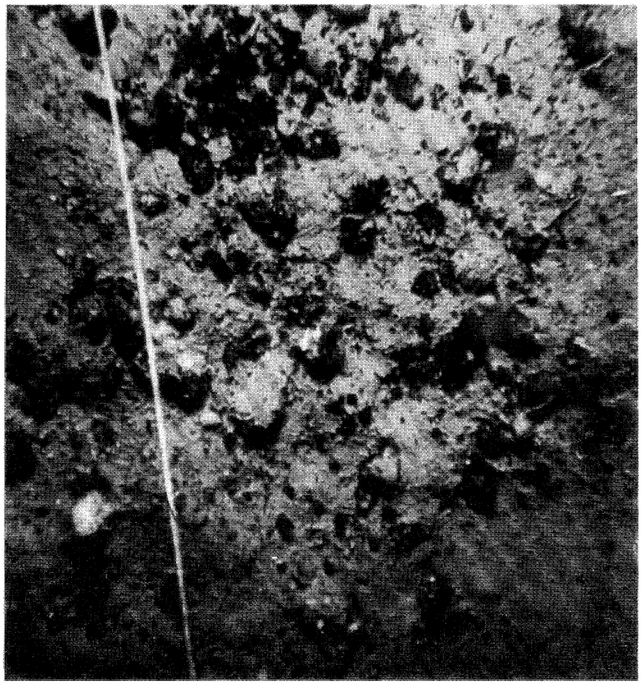

Figure 4. Phosphorite concretions offshore New Zealand.

2. Tasks and trends

The mutually related factors of the vast resource potential of ocean minerals are the severe natural conditions, the demanding technical tasks required to identify and exploit the mineral deposits, and the economic, environmental and political requirements for exploitation, quite apart from the legal uncertainty. By simply emphasizing the potential and neglecting the problems – as some overoptimistic delegates of the Law of the Sea Conference may have been tempted to do – nothing of value will be created. I shall therefore analyse some of the more important natural conditions and some of the tasks, problems and technical trends in an attempt to solve these problems. Working in the sea means protecting the sea. Environmental research and control are the technological framework for ocean mining and I shall try to give an account of them.

2.1. *Positioning*

Exact position fixing on and in the ocean, far away from land, is a novel and demanding task. Its significance is well understood by all terrestrial mine surveyors. They have developed, during centuries, their own art and profession. They would certainly look at their marine colleagues' problems with awe and respect.

Ocean mining presupposes the precise and repeatable identification of a ship's position on the sea and of exploration and mining equipment in the sea and on the sea floor. Positioning requirements within absolute geographical coordinates are of a range of 10–100 m. Requirements within a relative coordinate system of ocean floor transponders are of a few metres, sometimes of a few decimetres only. These requirements must be viewed against the background of traditional celestial navigation, sufficient for centuries to navigate a ship with the precision of some kilometres from one port to the other.

The help of artificial stars, navigation satellites, has improved the precision in remote offshore areas by a factor of 10 for a moving ship. When on station for an extended period of time, say 24 h or more, and upon receiving a sufficiently large number of good satellite fixes ('samples' in the statistical sense) accuracy can be further improved. Precision ranges of 100–200 m can be achieved. It is, however, difficult to maintain position exactly for an extended period of time. Offshore oil drilling is an example of the need to obtain and maintain an exact position.

Exploration for ocean-floor minerals and ocean mining, however, require movements of the ship along predetermined tracks. Because of the lack of sufficiently accurate short radio wavelengths in the more distant offshore locations, hopes concentrate on the future Global Positioning System (GPS) to become operational at the end of the 1980s. The system will include up to 24 satellites composed of three groups of eight satellites in three orbit planes at a distance of 20000 km above the Earth and an orbit cycle speed of 12 h. This arrangement will provide direct line-of-sight signals continuously from at least four satellites at any point on the Earth. A geographically well defined ground control system will work as the reference basis. It will receive the satellite signals, determine the orbits precisely and transmit and program the exact orbit data into the memory of each satellite. The satellite gives this information to any properly equipped receiver station and upon processing and comparing the signals from four satellites an accurate location of the receiver station can be obtained. Accuracies are expected to be ultimately in the range of a few metres.

Precise underwater positioning is being done and is being improved by acoustic short base-line and long base-line systems. The short base-line method uses phase difference measurements received by a hydrophone cluster from a sea-floor acoustic transducer. The long base-line method involves arrays of transducers on the ocean floor, and time–distance differences are measured. This requires a good knowledge of acoustical properties such as sound propagation within the water column. If proper corrections can be made, accuracies of underwater acoustic positioning may be within a few decimetres. This method has a limited range, about 1–2 times the water depth, and reliability is not good at present.

These few examples of precision requirements and precision achievements, even for non-military uses, highlight the technological background of the freedom of the sea. Until fairly recently it was impossible to determine exactly a position on the sea surface, let alone beneath it. Freedom in this context meant inaccuracy of a position. During the 1990s, when position-fixing on and below the sea will be possible to the extent described above, a different notion of freedom of the seas may evolve. It could be the freedom of an organized and controllable use of the sea, subject to certain rules but permitting everybody free access to venture into a risky benefit–cost relation. Technological developments in ocean exploration indicate the same trend.

2.2. *Exploration*

Exploration means in our case the detection and the delimitation of a minable deposit that is unknown or insufficiently known. Its method is inductive reasoning on the basis of samples, which are segments of information representing to a certain, unknown, degree the deposit. This statistical information gathering is highly susceptible to modern mathematical methods of information acquisition and information optimization. On the equipment side particular aspects of the environment have to be taken into account, which are, in deep ocean exploration, stringent, risky and expensive.

The two-dimensional nature of ocean mineral deposits at great water depths and economic constraints determine development trends and methods of exploration. Fast and wide, ‘planar’, coverages of high precision in order to make optimal use of ship time, the most expensive item, constitutes the main goal. A day of well equipped ship time costs £5000–10000. The full exploration of an ocean mine site, including the preparation for mining, may necessitate 500–1000 days of ship time.

Remote sensing, mainly by geophysical methods, with off-shore data storage and later on-shore data processing, helps to make better use of ship time. Offshore exploration thereby becomes more and more efficient in terms of data results per budget unit and time spent. Developments in electronics, data transfer and processing continue to assist considerably in this effort.

One example out of many is the U.S.-American Sea Beam bathymetric charting system. Developed for the Navy, it was made available for non-military uses during the late 1970s. Its acoustic transmitting–receiving arrays, installed perpendicularly on the ship's hull, send signals at 12 kHz to and receive echoes from the sea floor. The sonar signals are highly directional owing to phase interferences and gyro stabilization. The fan-shaped beam array covers the sea floor at a width of about 80 % of the water depth. It allows the real-time plotting of corrected sea-floor maps at high speeds, up to 19 km h^{-1}, and with a precision of up to 0.1–0.2 % of the water depth (figure 5).

Owing to the bipolar character of water molecules the sea constitutes a barrier (technically, a medium with a very high damping factor) for most electromagnetic wave propagation.

Water is on the contrary an excellent carrier of elastic waves. Underwater acoustic (short wavelengths, limited source energy) and seismic methods (long wavelengths, high source energy) have thus been developed. Both methods are either applied from the surface or from deeply submerged observation carriers. The latter method is associated with the problem of the cable for the transfer of mechanical forces, electric energy and information. Traditional marine cables have always been elements of weakness, posing operational problems and reduction of efficiency. Modern developments in direct current transfer of electric energy and development in plastics such as Kevlar fibres and in fibre optics help to solve these problems. An alternative would be an autonomous, cable-free observation fish. Energy storage capacities for propulsion and storage capacities for data are, however, restricted. The data transmission capacity of water for control data is quite limited (bandwidth and speed of acoustic waves permitting up to 5–20 kbits s^{-1}, depending on the water depth, compared with 100–300 kbits s^{-1} for coaxial cables or 500 Mbits s^{-1} for future fibre optic cables). Water is even more limiting for the real-time acoustic transfer of television or inspection information, or both (figure 6).

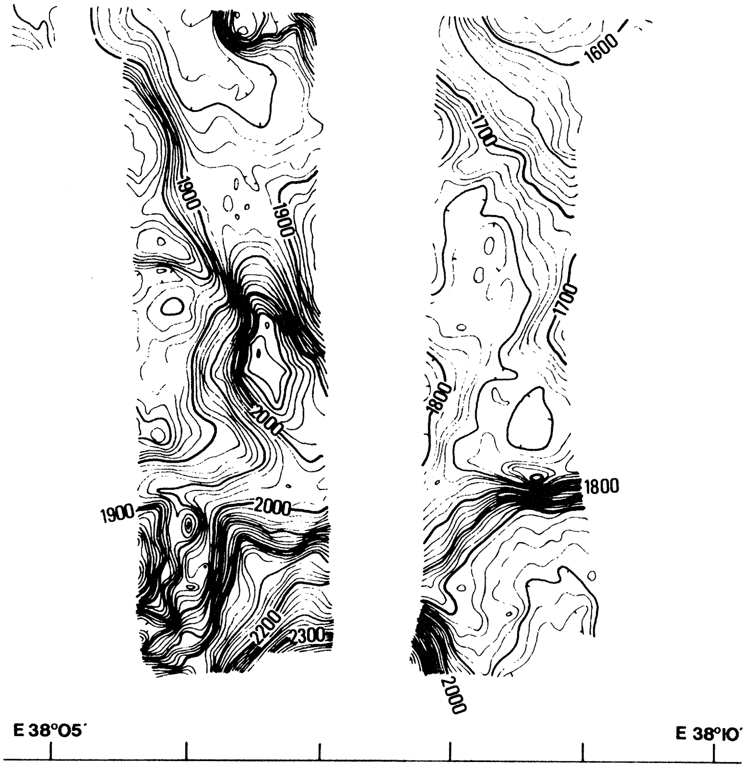

FIGURE 5. Seabeam sea-floor mapping (Atlantis II Deep, Red Sea).

Cable-guided observation fishes (figure 7) will therefore persist. Development continues to reduce the diameter of cables and at the same time to increase transfer capacities and reliability.

Sampling, in the sense of taking physical samples of the ore and subsequent laboratory analysis, although indispensable, will be reduced more and more to special tasks, mainly calibrating the various data gained by geophysical remote sensing. The technical methods and procedures of sampling become more automated, using buoyancy as the lifting force, as demonstrated by the various free-fall sampler techniques. Recovery of sea-floor sulphides or nodules in the sediment is achieved by specially actuated grab samplers such as the pneumatically driven sampler used for recovering phosphorite samples on the Chatham Rise.

Determination of ore contents *in situ* is possible by methods of neutron activation. Equipment problems and operational difficulties of sensors *in situ* in deep-water conditions have so far prevented the successful implementation of this highly desirable detection method.

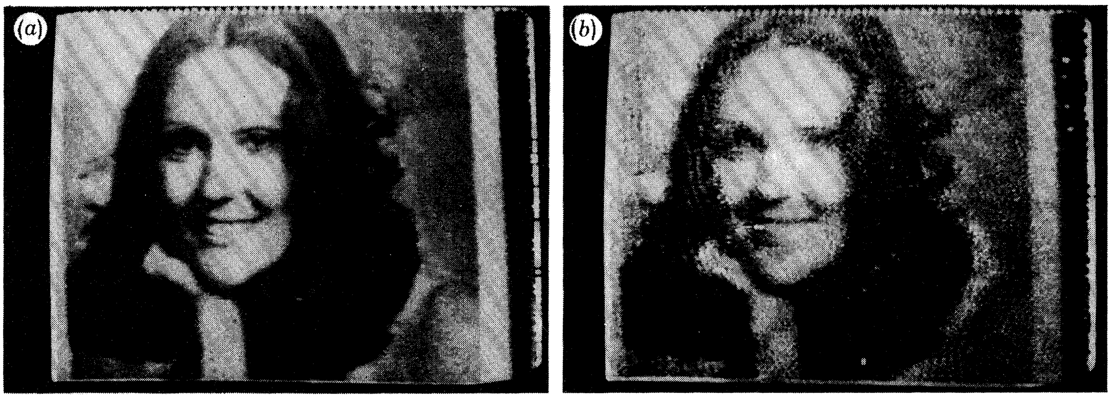

Figure 6. Television original (*a*) and image (*b*) after transmission through 2000 m of water (C.N.E.X.O.).

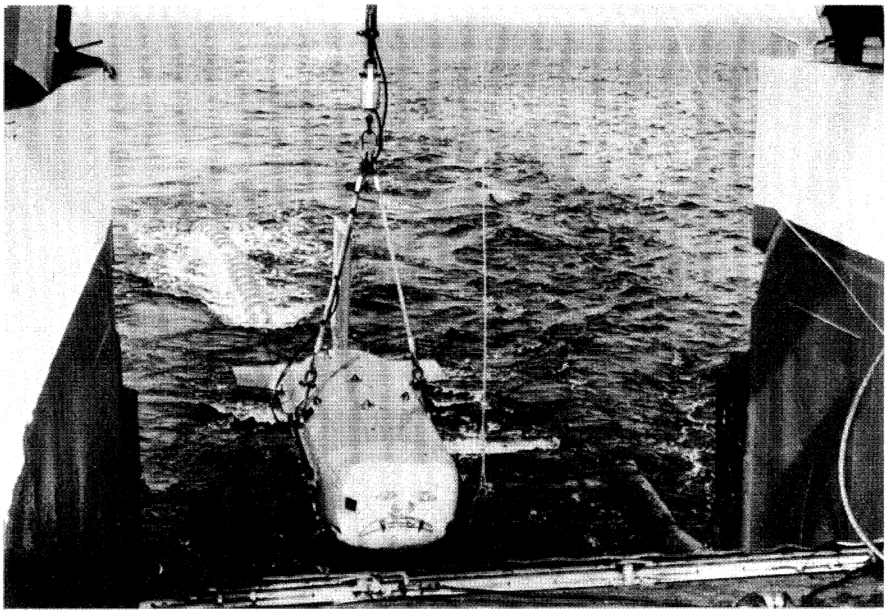

Figure 7. Deeptow, a cable guided observation fish.

Data collection and evaluation result in large data files. Powerful methods of modern statistics allow optimal use of the data for the most reliable determination of important deposit parameters based on insufficient sampling information. At the same time optimal future exploration procedures can be statistically determined and technically planned to obtain more and better information.

Despite the success and cost effectiveness of remote sensing methods and subsequent data processing by computers, the human eye, brain and even hand cannot be totally excluded from further prospecting and detailed exploration work. The outstanding results of recent research on hydrothermal phenomena long the northern section of the East Pacific Rise have shown this. Scientists in deep submersibles have discovered totally new underwater worlds, especially along the geotectonically active ridges and rises, with hitherto unknown environments and resources. Man, properly equipped and protected, remains the most versatile and redundant exploration system for complex details. The high costs and safety problems connected with manned missions restrict their application, however, to necessary research on such details.

2.3. *Ore collection*

The two-dimensional character of the ore body, its situation on an irregular sea-floor morphology with soft sediments, its variations in mass and grade and the great water depth are restricting natural conditions for any mining method. Mining economics and general resource policy require selectivity of ore mining and high pick-up rates. Substratum sediments and gangue materials are to be left at the bottom. The two-dimensional ore body and economies of scale require large collecting capacities. Collectors must therefore be wide and are difficult to operate from an altitude comparable with the altitude of an intercity passenger plane above the ground. Cutting of the ore can be performed by mechanical action supported by hydraulics, both in various design configurations (figure 8).

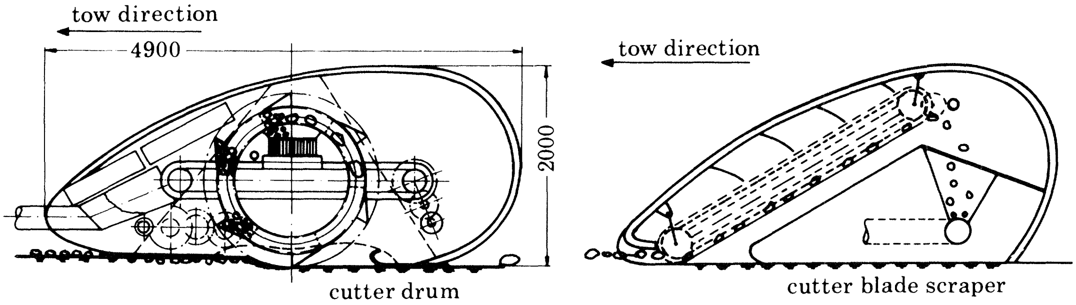

FIGURE 8. Design for a collector for nodule recovery. Dimensions are in millimetres.

Separation of the ore from the substratum and gangue can be done by screening, sieving and washing. Crushing can be performed by mechanical devices such as breakers. The tasks are well known in conventional offshore and onshore dredging. They have so far been handled in a rather empirical manner. Dredging on the deep ocean floor can no longer be performed by adding mass, strength and power. Skills from machine tool design and operation, the new theory of strength of plastic materials and field-testing of models are being applied to improve deep ocean dredge heads. The ultimate proof, pilot and commercial operations in several kilometres of water depths, will eventually see equipment that would be as different from shallow water equivalents as deep sea fishes from surface fish.

The above requirements amount currently to heavy structures of large dimensions. Widths of 20–40 m for nodule collectors are being investigated. High manoeuvrability and control, possibly with self-propulsion, are also required. The complicated robot vehicle fulfilling all the necessary requirements may not be operational on the ocean floor before the end of this century.

Collector devices should work, like all underwater equipment, without failure for a specified minimum time, say 6 months or more. Retrieval of a collector and its repair is a time-consuming, unproductive and risky operation. Technical reliability is therefore a fundamental requirement that can best be achieved by simplicity, this being more frequently the result rather than the start of lengthy and expensive development. The first (commercial) collector design at the end of this decade will thus be most probably of passive design, towed by the ship and the pipe string, with the sucking force of the dredge pump as the only dynamic element on the sea floor.

A collector dredge head towed by the ship and thus positioned by the ship's movement needs to be precisely located on the sea floor. Acoustic transponder positioning with an array between collector, ship and transponder is being applied. This is a combination of long base-line and short base-line methods, able to provide maximum reliability and precision, ultimately in the range of decimetres. Since such precision would far surpass the positioning accuracy of a dynamically positioned mining platform, an autonomously moved and controllable dredge head would be the logical next step of development.

2.4. *Ore lift*

Continuous transport of ocean minerals from the deep sea floor to the sea surface has been successfully tested by either pumping or air-lifting through steel pipes. The latter method involves the injection of compressed air into the pipe string at a certain depth. Upwelling of the air and the water mixture produces a lifting effect. The tests confirmed that pumping with a deeply submerged radial or radial–axial pump was more efficient in terms of technical throughput. Energy consumption is considerably less (by a factor of 2–5) for pumping than for equivalent airlifting. The latter also requires large pipe diameters in the upper part of the transport pipe string. Average pipe diameters need to be large anyway to permit sufficiently high flow rates and are in the range 60–80 cm. Still larger pipes result in too much weight to be handled easily and cause an excessive drag resistance for a dynamically positioned mining ship, especially if buoyancy modules will have to be added for hook load reduction.

Reliability and ease of maintenance, however, give air-lifting operational advantages. Design is much simpler. There are no moving parts under water, there are no internal pressure differences with resulting erosion problems, and there are no reaction forces as in underwater pumps. Erosion, cavitation and corrosion constitute considerable material hazards for underwater slurry pumps (figure 9).

Extended endurances of 5000–10000 h, necessary for economic operation, seem to be still far away. A solution could be bypass pumps, which would work with good efficiency and long endurance as they would be operated in seawater only. The stream of ore slurry is bypassed through a set of valves. This principle, quite attractive in theory, has, however, not yet been tested under offshore conditions.

The final decision for either pumping, bypass pumping or air-lifting will depend on future operational experience and particular project requirements.

Pipes are common steel pipes as used in the oil and offshore industries. Extensive experience in connector design, handling, and strength of material are available. Steel pipes are very heavy, however. For example, a 60 cm production pipe of 5000 m length weighs 2000–3000 t. Corresponding requirements for hook load capacities of the handling equipment are beyond the present state of available technology. Weight reduction could be effected by using fibre-reinforced plastic pipes (glass fibre, carbon fibre) if they could offer the equivalent strength and pressure capacities as steel pipes. The inherent disadvantage, that of low breaking strength at the connector intersection with the pipe, cannot so far be overcome.

The hydrodynamics of a production riser 5 km long being moved at slow but yet quite remarkable speeds (speed above ground up to 4 km h^{-1}, speed through water up to 7 km h^{-1}) are not at all well known. First tests have proved a quasi-verticality. This was due, apparently, to the most cautious advances during those first tests. Advances in ocean mining will require the establishment of more precise relationship between drag and mass coefficients – an ocean mining extension of Froude's theory on hydrodynamic performance and modelling.

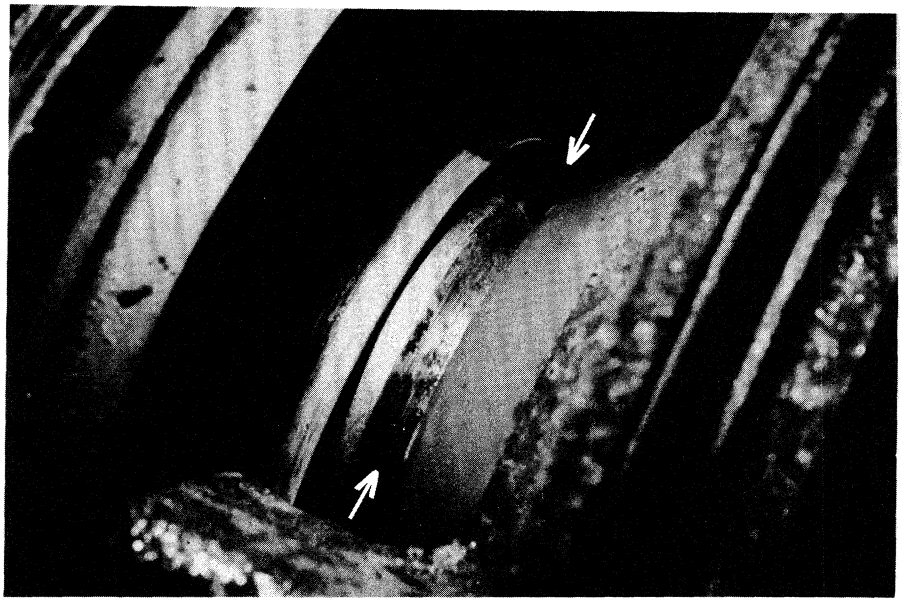

FIGURE 9. Erosion in an underwater slurry pump (Preussag/Worthington).

The transfer of electric energy to the deeply submerged pump station and to the collector implies another set of problems. Installed capacities of the pump station are in the range 20–40 MW and of the collector in the range of some 100 kW. Transfer voltages of alternating currents must thus be comparatively high, 5–10 kV, to transmit the required energy without too many transfer losses. There are problems of insulation of such voltages from the electrolytic medium of seawater and at great surrounding pressure. Although easily manageable in theory, practical problems of operation under offshore conditions have to be overcome. This holds in particular for cable connectors. These are usually oil-filled, deaerated and pressure-compensated boxes that are rather clumsy pieces of equipment. Oil-filled and deaerated rubber plugs with totally protected pins have been developed and offshore operators hope that these connectors will eventually take the place of connector boxes. Advances in thyristor regulation and control result in devices for high power input, small size and potential underwater application. This would permit the application of d.c. energy transmission and d.c. underwater electric motors. While sizes and masses of electrical power equipment could be decreased, reliability and controllability as well as insulation could be improved.

Still other methods of ore transport to the sea surface, such as the continuous line bucket dredge or free moving transport shuttles, seem to be either too simple or too exotic ever to become competitive with pipe slurry transport. Encouraging test experience has not yet been established for these principles. Some experts maintain that the use of buoyancy for ore lifting to the surface is the easiest and least expensive method. An analogous example may be quoted to demonstrate the point. In times of expensive energy, technical thoughts are being concentrated again on gas-filled airships for special lifting and transport tasks. And since buoyancy is the lifting principle in a liquid medium it may indeed become technically applicable.

2.5. *Mining platform*

The functions of the mining platform are storage and handling of mining equipment such as pumps, pipes and collector heads; offshore processing, storage and offshore loading of ores and concentrates; amenities for the technical and scientific crew; initial transport of equipment to the mine site; positioning of the equipment on the ocean floor; and mining. The design and operation of the platform are tasks in which the specific aspects and technological trends of ocean mining appear quite acutely: motion compensation for mining equipment at the moving surface, mobility and station-keeping ability of the platform, large scales and high investments, large innovative steps, reliability and safety of mining operations, automation and controllability, and energy economics of operation.

The platform envisaged has a ship-shaped hull, which best combines all requirements. Storage of ore and concentrates will require storage in the range of 10–100 kt.

The handling of mining and pumping equipment require hook load capacities and vertical compensation of hitherto unknown masses (2–3 kt). Motion compensation of the handling gear for the mining equipment (roll, pitch, heave) is another important requirement. Standard offshore drilling equipment with cable winches and derricks are not sufficient. Hydraulic vertical movements of the travelling and even crown block are required and have been successfully pilot tested. Automation of pipe and equipment handling can be best achieved with hydraulics. The future will therefore see hydraulic lifting gear, fully automated and safe, motion-compensated to a large extent and with just one supervisor in a remote control cabin instead of the present teams of roughnecks at hazardous work on the derrick floor.

An offshore processing plant may have to be installed. Last but not least, personnel will ask for convenient housing facilities to stay 2 or 3 months offshore for one tour of duty. These various functions will require a vessel of 100 kt displacement or more, dynamically positioned.

Although there is no limitation in building such a vessel, there is a major handicap in operating it economically for reasons of fuel economy. Installed power should be of the order of magnitude of 100 MW and diesel or residual fuel consumption at 100–300 t per day. In the central Pacific this would be very far offshore and far away from sources of cheap energy supplies. An ocean mining platform with a nuclear power plant seems to be the best answer. There is just one non-military experience of extended duration available for a floating nuclear power plant used for propulsion purposes on the German test vessel *Otto Hahn*. The industrial application of offshore nuclear power would thus be another large innovative step.

Offshore loading of ores and concentrates from the ocean mining platform to ore carriers is still another task of novel character. Skills from existing technologies in ore slurry transport and loading, offshore oil loading and in dredging and transport of dredging material through floating hoses will help to solve this problem rather quickly. The innovative barrier seems smaller than in many other aspects of ocean mining.

2.6. *Offshore processing*

Offshore processing may be required to dispose of ballast and gangue material. Offshore processing considerably improves the economics of ocean mining in some cases, and is being tried wherever feasible and necessary. Offshore disposal of gangue and residues at the mine site should be considered as a major advantage because environmental risks are not transferred to coastal areas, which are usually more delicate environments than the open sea. In addition and as will be shown below, disposal in the open ocean can be effected in a more controllable and acceptable manner than onshore or at the coast.

Polymetallic nodules should be dried to save transport costs. The need for process heat of low energy for drying would again justify the installation of a nuclear power plant. Further offshore beneficiation of nodules into a concentrate does not seem feasible at present owing to the complex oxidic and hydroxidic mineralogy of the nodules. The present state of the art could, however, be changed by advances in modern physical separation methods such as magnetic separation for diamagnetic matter.

Metal sulphides from the sea floor are readily processed offshore into bulk metal concentrates by fine-grain flotation and partial dewatering. Tests have shown the feasibility and advantages of offshore flotation of freshly mined and still surface-active, non-oxidized sulphide particles. Experts maintained only 10 years ago that metal sulphides with complex intergrowth of crystallites of sphalerite, chalcopyrite, pyrrhotite, siderite and including oxidic–hydroxidic minerals such as goethite, all in grain sizes of 2 μm and below, could not be concentrated economically. Residence times, energy and chemical consumption would be too high and recoveries and separation factors too low. Lengthy development and final offshore tests have shown the contrary. The negative effects of free surfaces of large and economic flotation cells of 100 m^3 capacity to be used in the future can be reduced by barriers and cell arrangement. Seawater turned out a better medium for offshore flotation than originally expected.

Recoveries of about 60–70 % so far obtained are not satisfactory. Further improvement to above 80 % would be highly desirable but will require extensive additional research and technological development. Fines of grain sizes below 1 μm and even below 0.1 μm need to be agglomerated by collector chemicals such as polymers, to be later floated by fine-grain flotation.

Dewatering of fine-grained and surface-active sediments or concentrates by solid–liquid separation is difficult owing to an unexpectedly high froth formation. Eventually, mechanical or chemical (or both) methods will be developed, however, to avoid or destroy such froth formation.

2.7. *Instrumentation and control*

Extensive remote control for all process steps, on the sea floor, in the pump and pipe string and on the mining platform, is technically a prerequisite and an economic requirement for successful ocean mining. Ore recovery from the sea floor lends itself to automation and control, similar to open pit mining on land and more so than in underground mining. Technical accomplishments in electronics provide tools of ever-increasing precision, complexity and lower cost to comply with this requirement.

Data monitoring for deep-water application has to comply with the pressure problem: 200–600 bar (20–60 MPa), depending on the ocean mining problem. Water temperatures are low, a few degrees above 0 °C, in nodule exploration and mining. Hot brines of above 60 °C give additional environmental problems to data monitoring and electronics in the special case of the Atlantis II Deep development project. The main task, however, is constant and precise flow analysis at the collector or dredge lead. Density, solid content and speed are essential parameters. Whereas acoustic, electromagnetic or nuclear radiation methods have been adopted for many onshore process control applications, their reliable use for deep water and remote control is still far away. Even more demanding requirements such as the online metal analysis of a mining flow – not yet realized in most onshore operations – should be tackled and solved in the more distant future.

Data transmission by low-voltage cables, so far the weak link in the chain, is poor because of easy disturbance by electromagnetic fields, connector and cable insulation problems and mechanical stress. With the advent of optical fibre transmission, many of these problems will be overcome at the same time as the transmission capacity of thinner cables increases.

Microprocessors are increasingly used to establish decentralized data processing and control capacities. They are thus taking the burden of crude data transfer away from transmission links. Microprocessors on just one single card as the standard 'Europe card', having 64 kbytes or multiple storage capacity can be easily encapsulated. Energy supplies are at low voltage, 5–12 V, which constitutes a considerable advantage for underwater applications. Redundant energy supplies by cadmium–nickel cells can be provided, which would permit fail-safe operation of up to 6 months. Monitoring tasks such as data sensing, integration and compensation of ore collecting or slurry transport *in situ* can be handled, including monitoring of viscosity, transport density and optimum energy supply. The central computer or computers are being kept for significant data processing tasks such as (digital) control, process optimization, data formatting and storage.

Software for process control has been developed with hardware to such an extent that real-time processing, even for the most complex processes, is already now common practice.

Whereas the total automation of ocean mining seems feasible, there is currently little operational experience. Software and hardware for total automation will ultimately cost little, but the learning process to arrive at total automation will be very expensive.

2.8. *Transport and infrastructure*

Transport of ores or concentrates from the offshore mine site to a port for further treatment and transport of supplies to the offshore mine are technically straightforward, without any particular aspects of new technology. The proper organization of transport and supplies will, however, significantly influence the economics of any ocean mining project: offshore processing of ores, intermediate storage of concentrates and the reduction of expensive transport movements are important requirements (figure 10). The same holds for personnel. Frequent crew changes over distances of several thousand kilometres would seriously impair the economics of any project. This is another reason why the technology of ocean mining must be geared towards automation.

The cost-effective organization of transport of personnel, material, equipment and information will be a prerequisite if ocean mining is to be competitive with onshore mining. An advantage of ocean mining is the reduced need for infrastructural development compared with mines in remote land areas. There are no roads and railways to be built, no particular energy supply investments, housing facilities or airport to be provided. The infrastructure for ocean mining is constituted by seaports, which are usually available. This advantage on the capital cost side could be offset by excessive operational costs for long-distance transport.

2.9. *Onshore production*

Polymetallic nodules or ocean-floor metal sulphides contain many metals. They show a varying and not yet fully understood mineralogy. They are therefore considered to be complex ores of a bulk character. Salt and water content have also to be taken into account. Standard metallurgical methods to extract the valuable metals – although basically feasible – proved uneconomic. Investment and operating costs for salt-free washing, drying, pelleting and other steps of ore and concentrate preparation for conventional pyrometallurgy were found to be prohibitive. New routes, composed of basically known single steps, are now being developed on the basis of bench-scale tests. Pilot and commercial experience is completely lacking, however, for this technically and economically most important last step of ocean mining. About half of all the investment required for a complete ocean mining venture will be for a polymetallic nodule smelter.

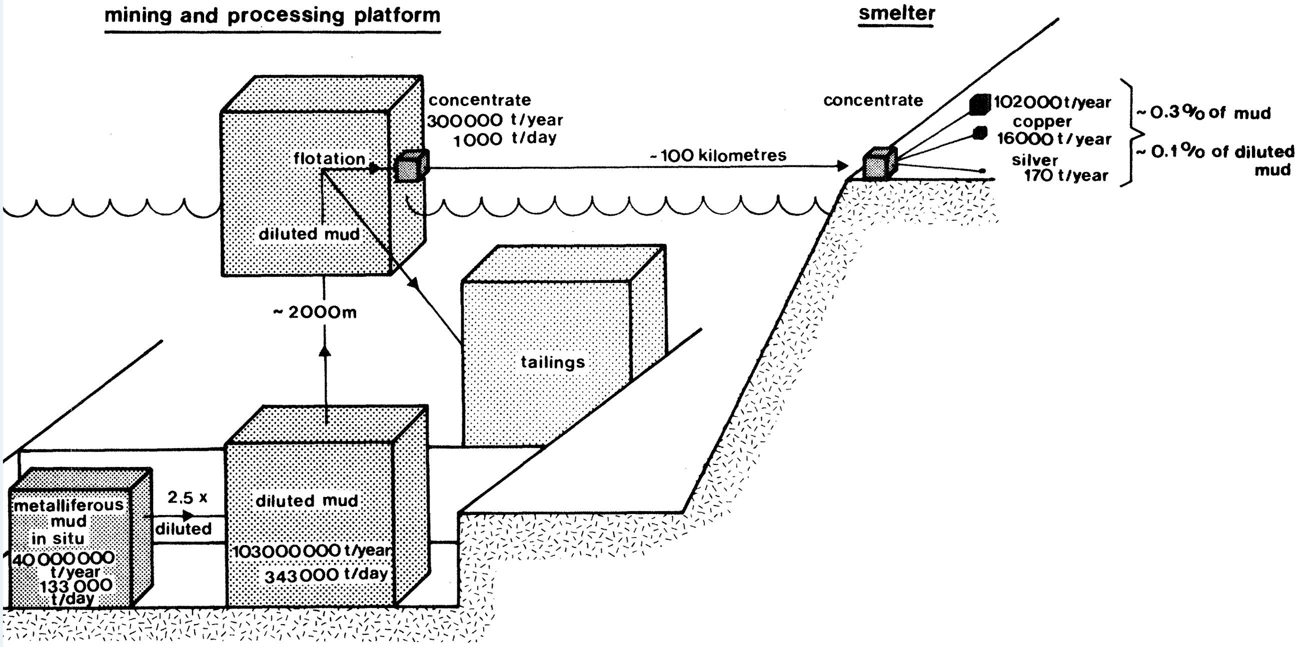

Figure 10. Transport volumes for the Atlantis II Deep project. Cubes correspond to expected true volumes.

A major criterion for the design and location of a metallurgical plant at a coastal site will be energy supply and availability. Metallurgical processing is inherently energy-intensive. Process routes with low energy consumption, or energy consumption in the form of a cheap residual fuel, or the location of a smelter close to cheap energy, will be preferred. The availability of cheap gas in New Zealand, for instance, could make this country develop into a processing centre for polymetallic nodules in the southwest Pacific. The availability of cheap energy in Saudi Arabia is one reason why the energy-intensive project of ocean mining and subsequent metal extraction from sea-floor sulphides in the Red Sea may become the first economic deep-ocean mining project in the world.

Floating production plants for the offshore production of oil, gas and other raw materials have become a popular theme in technological discussions and even, to some extent, in reality. Process routes and equipment are being adapted to offshore conditions to cope with reduced space and masses, corrosion, motion influences and different installation and maintenance requirements. A floating metallurgical plant, however, seems to be far ahead. Motion influences are more significant than in hydrocarbon process technology. Metallurgists know the severe problems that slight imbalances or deviations from the vertical or horizontal of only 1° may pose for refractory coatings of converters and reduction vessels containing molten metal and ore fluxes. If hydrometallurgical processes are used, electrowinning of the metals would seem difficult for adaptation to floating plant conditions.

Another question of basic significance, technically and commercially, will be the scope of metal production: which metals are to be produced, which metals would be better discarded? It seems to have become the internationally accepted understanding of most metallurgists – after lengthy discussions – that four metals in the nodules should be produced: nickel, copper, cobalt and manganese, possibly together with molybdenum. Economies of scale clearly indicate large production for one single operation. Orders of magnitude would be a yearly production of 40 kt of nickel plus equivalent amounts of the other metals, requiring about 3 Mt of nodules to be mined annually.

The availability of possibly cheaper sources of metals from the deep ocean floor (in the sense of being cheaper than future land supplies) will very probably influence the metal industry. This holds, in particular, for manganese as an alloy agent for low-cost steels and to some extent for nickel and cobalt. Alloyed steels, needed for industry, may thus become cheaper than they are today or, rather, could be expected to command a more stable price in a generally inflationary world.

2.10. *Trends in ocean mining; economic aspects*

Most of the scientific and technical elements required to comply with the difficult natural conditions and demanding technical tasks described above have already been tested. The feasibility of a nuclear power source for a commercial ship or a test mining system for polymetallic nodules or sea-floor sulphides are examples. Feasibility has been shown for collector design, instrumentation, offshore flotation or submerged pumping.

The major requirement is therefore to scale up these test experiences to commercial sizes and operate them under adverse offshore conditions for long periods. Scale factors are in the range 50–100. Extended pilot and demonstration operations are thus needed as intermediate steps to reduce scale factors to more controllable sizes of 5–10 per step. Demonstration operations will furthermore help to test the system reliability and to learn more about the reliability of system components. The capability of a technical system to work without breakdowns is particularly important for offshore operations and can only be established by long and expensive offshore experience.

One significant example is offshore corrosion, or, in proper technical terms, fatigue corrosion in a chlorine environment. Most steels do not have a sufficient residual strength in the low-frequency load cycles and high chlorine contents of the sea (figure 11). When this phenomenon was first observed, tests were run in laboratories all over the world to simulate, with higher frequencies, fatigue corrosion phenomena. It took quite some time, until the 1970s, to detect the significance of the low cycle of natural ocean waves on the fatigue resistance of steel. Meanwhile many offshore structures, all over the world, had shown severe corrosion after some 10–12 years of operation, or about $2-4 \times 10^7$ load cycles.

Scaling up by large factors and technical trials to obtain reliability have to be performed in what should be thoroughly understood as the technically most demanding environment:

the water–air interface, the ever-active sea surface, and the soil–water interface, the far distant sea floor. Learning is more expensive here and takes longer than onshore.

While research and technical development have so far required budgets of the order of £10 M, the next step of demonstration operations will require research budgets with orders of magnitude ten times larger, at least for the polymetallic nodules. The last step, commercial operation, requires investment and operating budgets again ten times larger, amounting to an order of magnitude of £1000 M.

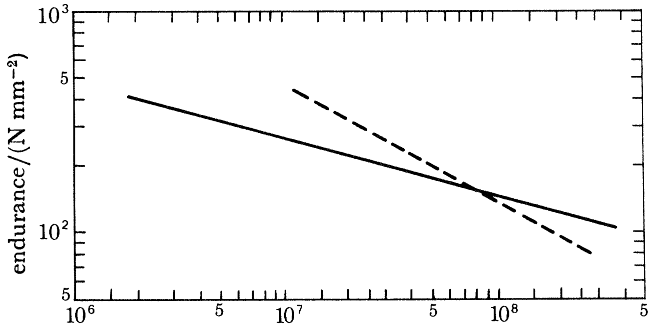

Figure 11. Wöhler curve, fatigue strength of steels in seawater.
——, Theoretical endurance curve; – – –, experimentally established endurance curve (at 5 Hz).

These costs must be viewed in the proper perspective. Metals are not oil and, being traded in true markets, have little chance of developing into anything equivalent. High risks are therefore not balanced by the possibility of high profits as in offshore oil. The value added for an offshore oil project in medium deep water, as in the North Sea, would be 100 times that for an ocean mining project of equivalent investment.

This assessment of ocean mining is the result of more than 10 years of scientific research, technical development and economic evaluation. But there are hopes of obtaining at least somewhat higher metal prices in future: the depressed metal markets for almost a decade have led to a lack of exploration, mining and metallurgical investment. Further development of mining for metals such as ocean mining seem to be possible only on the basis of improved metal prices to balance the massive development budgets and investment risks. The perception of these factors may have resulted in the constant postponement of forecasts for the commencement and development of economic ocean mining.

Ocean mining should in future compete with traditional land mining. Although there are chances of ultimate competitive advantage, one should always remember the land mining has developed an advantage in skills over centuries. Administrative production controls for ocean mining, however, would be detrimental to the world economy and would only help to sustain existing production structures artificially in a few countries such as Canada or the Congo. Compensation payments, to be drawn from royalties on truly competitive ocean mining, would be a much better concept to help adjust structures in developing countries.

3. ENVIRONMENTAL PROTECTION

The oceans constitute the world's largest and yet only partly understood environment. Its significance for the origin and development of life, for the climate on Earth and for geological processes is only beginning to emerge. Its protection, in the sense of intelligent environmental management and control, thus seems to be a task of centenial scope. It is good to be able to report that the nascent ocean mining industry has acknowledged its responsible role right from the beginning.

3.1. *The Red Sea model*

Understanding the physical, chemical and biological processes of the ocean environment should be the first step for ocean environmental management. Responsible environmental policies should be formulated and implemented on the basis of scientific, technical and social evidence, rather than being designed to catch votes from the electorate, which seems to have become the general abuse of democratic societies.

Research on the ocean environment by baseline studies before mining, specifications for technical protection measures for mining and steps to control the environment during and after mining have been most comprehensively promoted for the Atlantis II Deep Project in the Red Sea. The far-sighted policy of the Saudi Sudanese Red Sea Commission and funds for environmental research provided by the Saudi Arabian and the German governments have permitted a programme of environmental research and protection for ocean mining which may well be unique in the world. It will thus be briefly outlined here to conclude the more general requirements for environmental control of ocean mining in other areas. It may be interesting to note that of the budget allocated for environmental research in the Red Sea about one half of the total for exploration, mining and processing was spent on environmental research and protection.

3.2. *Ocean environmental research, baseline studies*

Relatively little was known about the marine environment of the Red Sea before the Red Sea Commission started its resource development programme in 1976–7. Some broad concepts had been formulated based on very sporadic and technically limited measurements. One of these concepts, concerning the general water current and exchange pattern, suggested a surface inflow of fresh ocean water from the Indian Ocean, intensive evaporation, sinking down of the seawater with a higher density and a slow flow back in the deeper water strata. A comprehensive programme to investigate the physical, chemical and biological environment of the central Red Sea in view of eventual ocean mining activities was therefore performed from 1976 to 1981 on behalf of the Red Sea Commission and the German Ministry of Research and Technology. Many companies and research institutions in Saudi Arabia, the Sudan, the U.K. (Imperial College), France, the U.S.A. and Germany are involved.

Physical oceanographic observations concentrated on numerous Eulerian and Lagrangian current measurements in the area of the future mine site, the Atlantis II Deep, and across the central Red Sea. Although the many million measurements have not yet been integrated into a satisfactorily representative numerical model of currents one can already see a rather complex current pattern. Surface waters, under the influence of the prevailing NNW winds, flow predominantly in a SSW direction with speeds up to 4 km h^{-1}. Near-surface waters, on the contrary, flow northwards as predicted. Current speeds are up to 1 knot. The deeper water, below 300 m, flows northwards in the eastern part of the deeper Red Sea, and southward in the western part. Current speeds are low or very low, 10 cm s^{-1} to virtually zero. This pattern is, in addition, subject to further regional and seasonal variations. The central Red Sea constitutes an area where northern, subtropical climates and southern, tropical climates intersect. These facts, together with water movements from the Indian Ocean and the irregular topography of the ocean-floor, result in the complex current pattern. Current gyres have been observed, e.g. by tracking neutrally buoyant floats. They remained on circular tracks in the area of the Atlantis II Deep for days and even weeks before leaving the area tangentially towards the north or the south (figure 12).

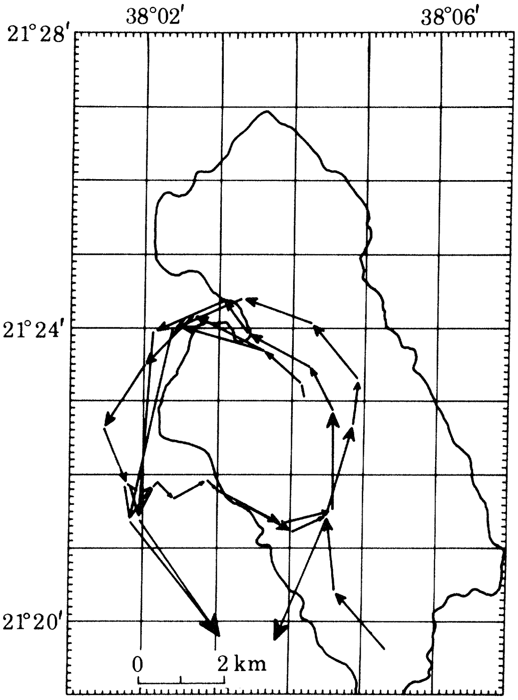

FIGURE 12. Current pattern above the Atlantis II Deep, at 1200 m water depth.

The low nutrient content (nitrogen, phosphorus) was confirmed in more detail together with the high salinity of almost 40‰. An interesting find was the high background content of mercury in the western part of the observation area (figure 13). Deep-sea shrimps from close to the Atlantis II Deep have been found to contain mercury at up to 7 μg g^{-1}. Surface fish, being eaten by the local population on the Sudanese coast, were found to have mercury at 2 μg g^{-1} in one instance, whereas the maximum permissible level for edible fish is defined by most national authorities as 0.5 μg g^{-1}.

Biological baseline research concentrated on the main offshore communities, plankton, benthos, nekton and, to some extent, the coastal reefs. Ecotoxicological investigations in connection with the influence of released tailings on the marine fauna have been performed. The following summarizes the extensive research efforts.

The reefs on the Saudi Arabian and the Sudanese coasts are a very rich and almost self-contained marine environment. Tailings, turbidity currents from mining or accidental discharges of sediments or concentrates should not disturb these unique and famous natural gardens. (The real dangers are vast development programmes for ports, industrial centres with effluents of desalination, and industrial plants and shipping lanes in the Red Sea and along the Saudi coasts.)

The vertically migrating plankton layers in the Red Sea (water depth during the day 400–700 m, during the night 100–200 m) are active producers of biomass and should be protected.

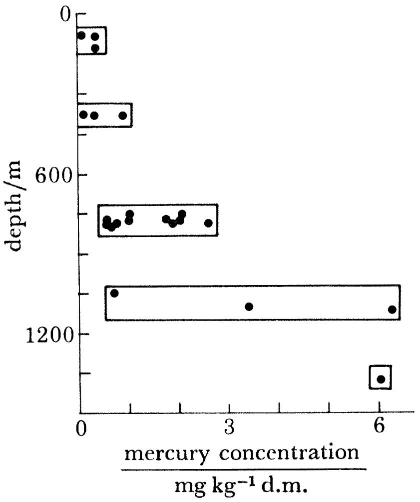

FIGURE 13. Natural mercury content in bottom-dwelling fish caught at different depths in the central Red Sea.

Benthos and offshore nekton are very sparse compared with the open ocean. This is due to the limited food supply and the harsh environment (high salinity, high temperature, low oxygen content due to absence of fresh polar bottom water). Sea-floor populations in 2000 m of water depth, such as various species of meiofauna, are as poorly distributed as in 5000 m of water depth in the open ocean. The hot brine area does not show any sign of marine life at all.

Ecotoxicological damage from tailings or freshly mined sediments can result from the spontaneous release of heavy metals (Zn, Cu, Hg) from the sulphidic mineralizations. Weathering (oxidation) reduces this limited danger fairly quickly. A threshold value of 1 mg l^{-1} for particulate matter from tailings in Red Sea water has been determined as tolerable.

3.3. *Protection engineering*

The technical answer to the compromise of economic ocean mining in the Red Sea and protection of the marine environment as briefly described above is controlled deep disposal of tailings. This has been tested successfully during the pre-pilot mining test in 1979 in the Red Sea. Disposal was performed through a pipe of 400 m length and 6 in (*ca.* 15 cm) diameter installed at the bow of the test mining ship. The pressure of the discharge pumps was 6 bar (0.6 MPa). The tailings flow descended almost vertically from the truncated lower end of the pipe to a water depth of 600–800 m (figure 14). At this depth a diffusion cloud developed that was transported away by the currents, mainly to the north, for ultimate sedimentation in an area of about 1500 km^2 (approximately determined by tracer tests). Final and complete sedimentation took about 50–60 days.

To be on the safe side, a 600–800 m long disposal pipe is planned for future operations (pilot mining operation, eventual commercial operation) (figure 15). The diffusion cloud should

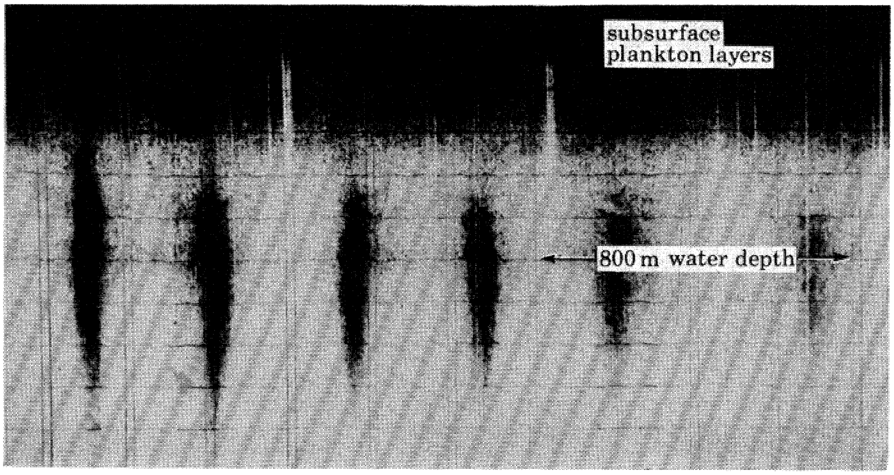

FIGURE 14. Tailing plume in the deeper Red Sea.

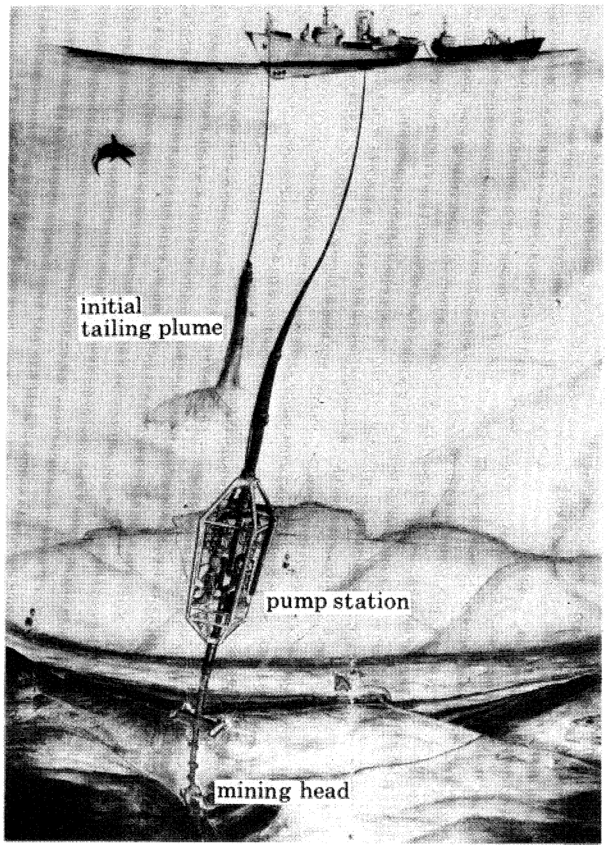

FIGURE 15. Concept of the pilot mining operation in the Red Sea.

then develop at 1000–1500 m of water depth, well below the active plankton layers and away from currents that may reach the coast. At this water depth, disposal would predominantly be contained in the Red Sea Central Trough in an area of 2000 km^2. The presumed resedimentation of the deposit by a few centimetres per year does not constitute a problem. Containment, dilution and controlled resedimentation will thus be achieved to an extent that seems similar to or even better than for conventional sand and gravel dredging in shallow and bioactive seas all around the globe.

3.4. *Control*

The straightforward method of disposal of mining and flotation tailings promises to protect the delicate marine environment of the Red Sea almost completely. Noticeable lethal effects on the fauna in the water column can be excluded. The influence on poorly developed benthos will be restricted to the areas of increased sedimentation and to species that cannot cope with the sedimentation. Repopulation can be assumed for these cases.

The prediction of the environmental impact, however, relies on limited observations. Environmental effects should also be observed during the next steps, the pilot and commercial operations, to investigate possible long-term effects and the influence of noticeably larger volumes of tailings. Subsurface buoys, monitoring the distribution of the disposal cloud by means of nephelometry, will be installed. Upwelling is not expected owing to the stable layering of Red Sea waters but will be closely investigated by various physical and chemical methods. Further tracer disposal and sedimentation tests are planned. Constant sampling and analyses of typical fauna such as deep-sea shrimps will additionally help to monitor all eventual long-term environmental effects, although they seem to be rather improbable.

3.5. *Conclusions for other ocean mining ventures*

The environmental containment of possibly negative influences and the control of ocean mining seem possible first by investigating and understanding the environment and then by applying adequate and effective technical methods of environmental protection. This is the preliminary but extensively researched result for the enclosed ocean basin of the Red Sea, which has a particular and delicately balanced marine environment. It therefore also seems to be applicable for the open oceans.

The environmental situation in the open ocean is usually better: the water depth is greater by a factor of 2–3, current régimes are different (more uniform), replenishment of groundwater by the polar water currents containing nutrients and oxygen helps to bring about the generally more vital environment of the open ocean.

Dredging of polymetallic nodules interferes with the benthos at the dredging sites. Repopulation will overcome this limited problem in a way similar to all dredging sites for sand, gravel or tin placers. A surface disposal test of sediment slurries from polymetallic nodule mining in 1978 has shown relatively fast sedimentation. The disposal cloud to be observed behind the test mining ship was never longer than a few hundred metres, indicating sinking velocities of the sediments of 10–20 m h^{-1}. A disposal pipe, shorter than for the Red Sea project but extending below the euphotic zones, could exclude surface effects. Upwelling of nutrient-rich bottom water will influence the surface fauna and flora over a limited area. Although this effect should not be detrimental because it increases biological activities at the surface, it is to be investigated in more detail.

4. Summary: the need for innovative talent and entrepreneurial development

A basic question is whether ocean floor minerals are worth the extensive political effort needed to constitute a model for a future New Economic Order with more social justice and democratic participation and, last but not least, sufficient efficiency for the general welfare of all mankind.

If the international community wishes to benefit from the ocean mineral potential – and, indeed, everybody should eventually benefit from it – the international community should organize a régime conducive to the creation and successful performance of such development. This and only this would constitute a true responsibility for the common heritage of mankind.

There is a long, difficult and expensive learning process for economic ocean mining ahead. Whereas the vast potentials of the ocean-floor minerals are known to some extent, the difficulties of exploration, mining and environmental protection are becoming more acute. Whereas basic solutions for these problems have been identified, little is known about operating at the necessary large scale and for a long time. With scale-up requirements by factors of 100 (one hundred!) and under offshore conditions, future experience will be comparable with the most ambitious space programmes. The future of ocean mining requires therefore exceptional human input, responsibility, imagination, capital and, last but truly not least, international consensus.

Most important, therefore, are innovators: scientists, engineers and managers able and willing to undertake the effort. Capital in the order of £1000 M will be required for further large-scale demonstration testing and the initial investment schemes. The risks of failure are considerable.

Innovators from industrialized and underdeveloped countries should thus be attracted to the challenging tasks of ocean mining, and not be distracted by the provisions for automatic expropriation of their skills that are now planned. Risk capital should be attracted by giving it the opportunity for adequately profitable use. The flow of money to the international community, on the basis of adequate taxation, should be envisaged only for those more distant years when the profitability of investment has been demonstrated.

Developing countries who wish to attract industries grant tax-free periods for the first years of operation. It is difficult to understand why the same countries favour an international régime of the deep sea that implies discriminating taxes for a non-existent industry. Compared with the risks and problems of investment in a developing country the many risks of offshore mining seem tremendous.

The role of the International Seabed Authority should then be focused on global tasks of safety, research and protection of the ocean environment and orderly and legitimate administration of the competitive efforts of private initiatives. It is a well established fact from industrial development over 200 years that initiative and competitive efforts have produced more products, services *and taxes* for the benefit of everybody than over-administered organisations. The latter serve mainly to support some officials and their political and ideological purposes. A monopolistic enterprise operating as a resource company on behalf of the Authority has every chance of growing into a huge, infertile overhead, not producing but only costing the international community tax payments.

Enterprise is thus the keyword for further development in ocean mining; enterprise not with the recently adopted ironic understanding of a world monopoly working on behalf of the

Seabed Authority. Such a venture should rather be qualified as a 'non-enterprise' because it would be passively and artificially nurtured by finance and technology transfer from industrialized countries. Nor should enterprise be understood in the antiquated sense of nineteenth-century economy with all the bad experiences of early capitalist development. Rather, the term should emphasize the opportunities for improving man's quality of life, and the prospects of overcoming the many obstacles by competitive effort, responsibility, efficient management, control and participation. The organizational form could be in international joint ventures, to give just one example, in which parties from industrialized and industrializing countries work and learn together on the basis of joint responsibilities.

Such entrepreneurial development would demonstrate that there is not the lack of opportunities in the world that many politicians or economists claim as the reason for the present economic slowdown. Ocean mining could well become the example to disprove this for the true benefit of all mankind. While the negotiations for an international régime on sea-floor minerals have come to a halt and bilateral negotiations have started, I hope that this pause may help to ultimately produce a working international consensus for the development and eventual use of ocean minerals in the 1990s and beyond.

I wish to thank the Royal Society for giving me the honour and pleasure to present this paper. If this summary report was successful it is due to the merit of my colleagues and the many outstanding personalities in institutions and corporations with whom I have had the privilege to cooperate. I may mention in particular Zaki Mustafa, the Secretary General of the Red Sea Commission, Friedrich Wilckens of the Federal Ministry of Research and Technology, and Günther Sassmannshausen, the Chairman of the Board of my company, Preussag AG. All ideas of this presentation reflect, however, my personal views.

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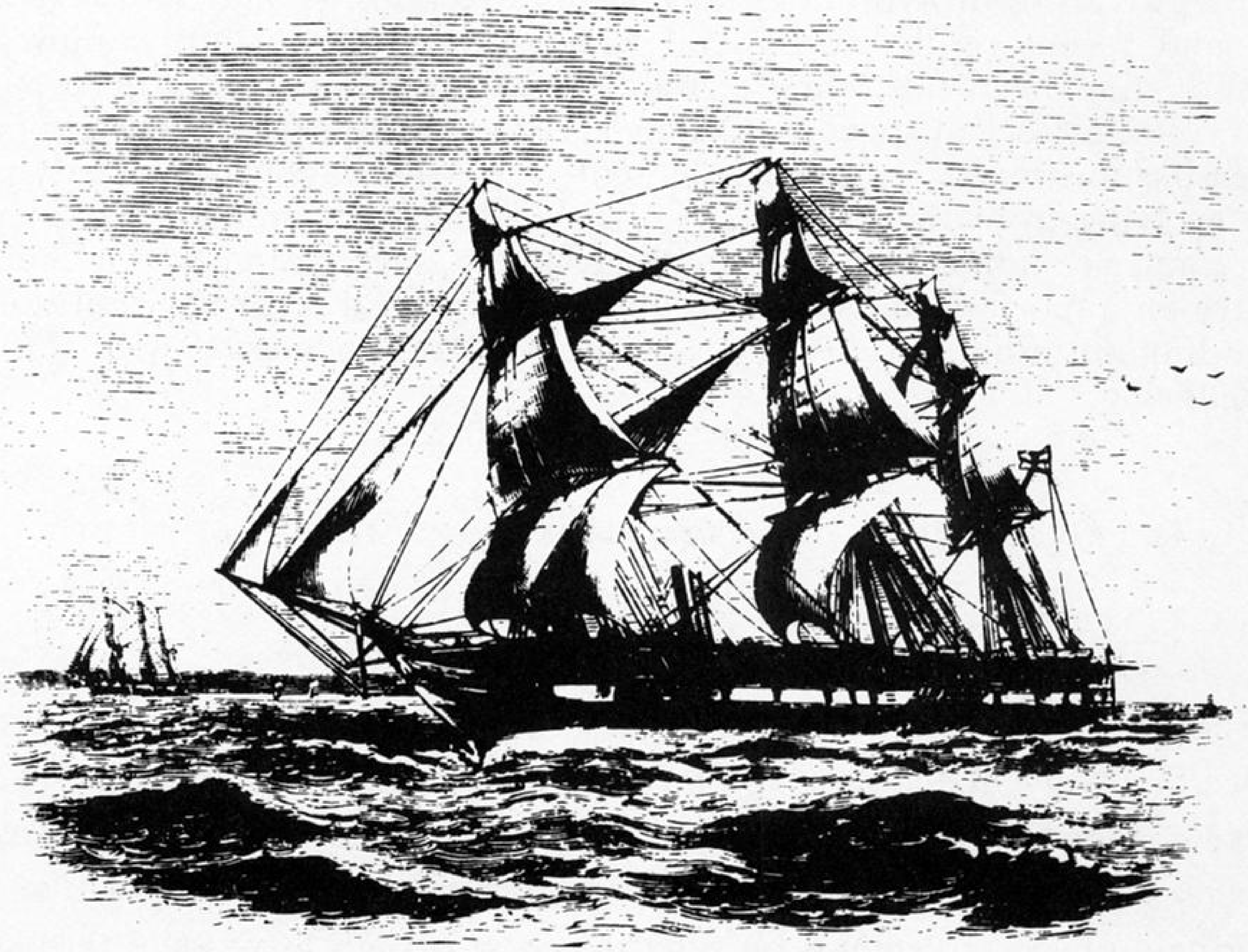

FIGURE 1. H.M.S. *Challenger*.

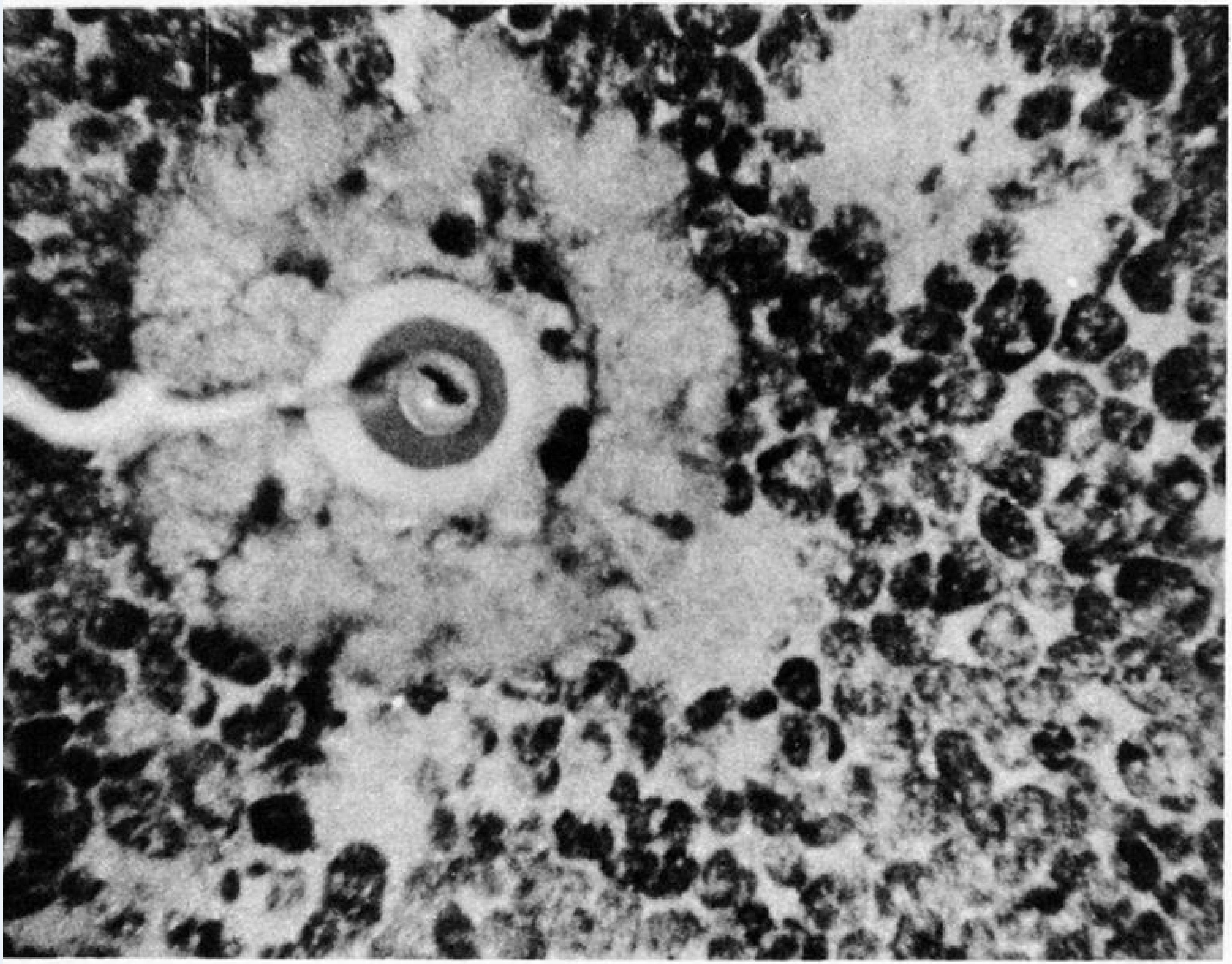

FIGURE 2. Polymetallic nodules on the Pacific sea floor.

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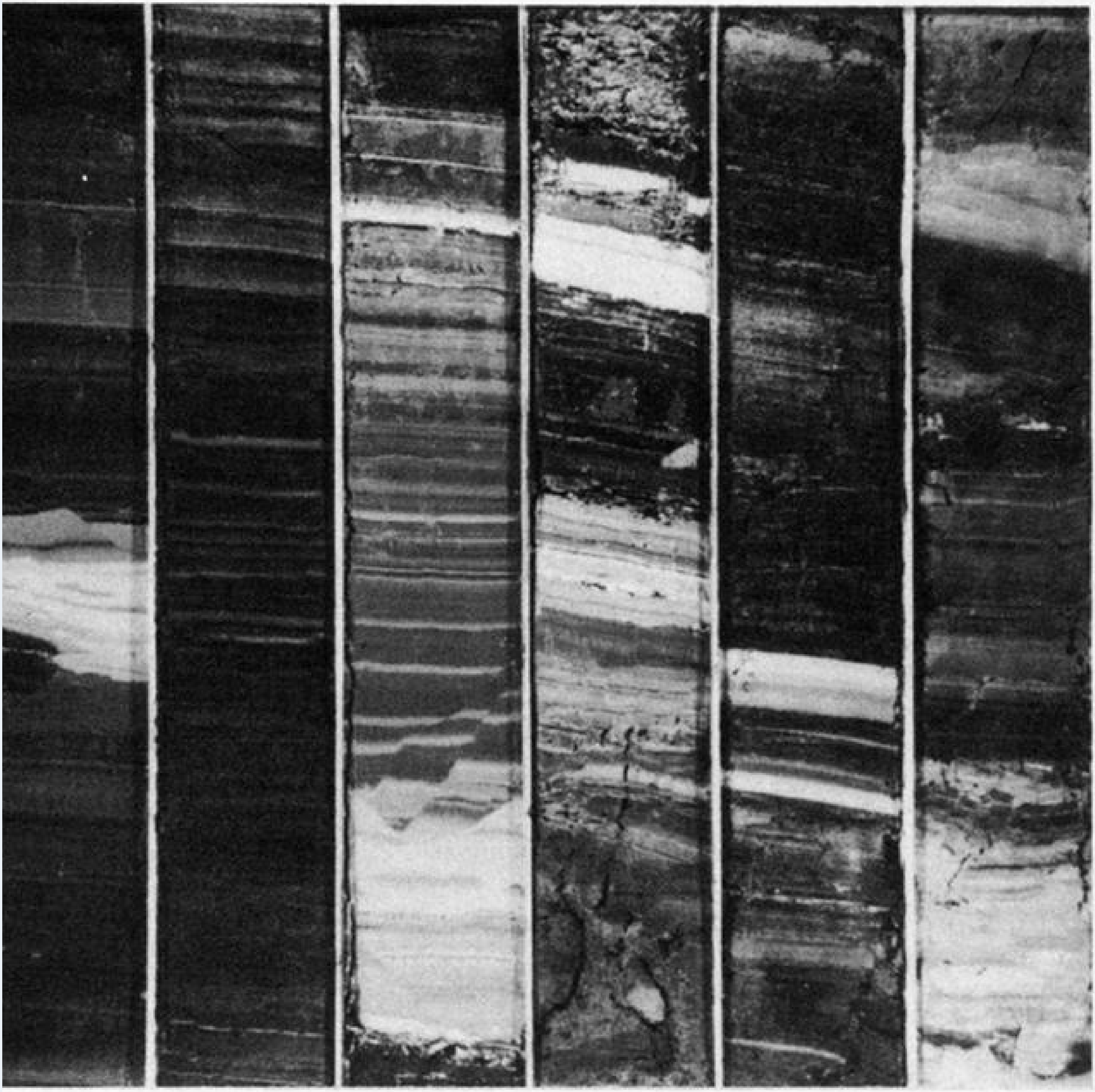


FIGURE 3. Metal sulphides in the Red Sea.

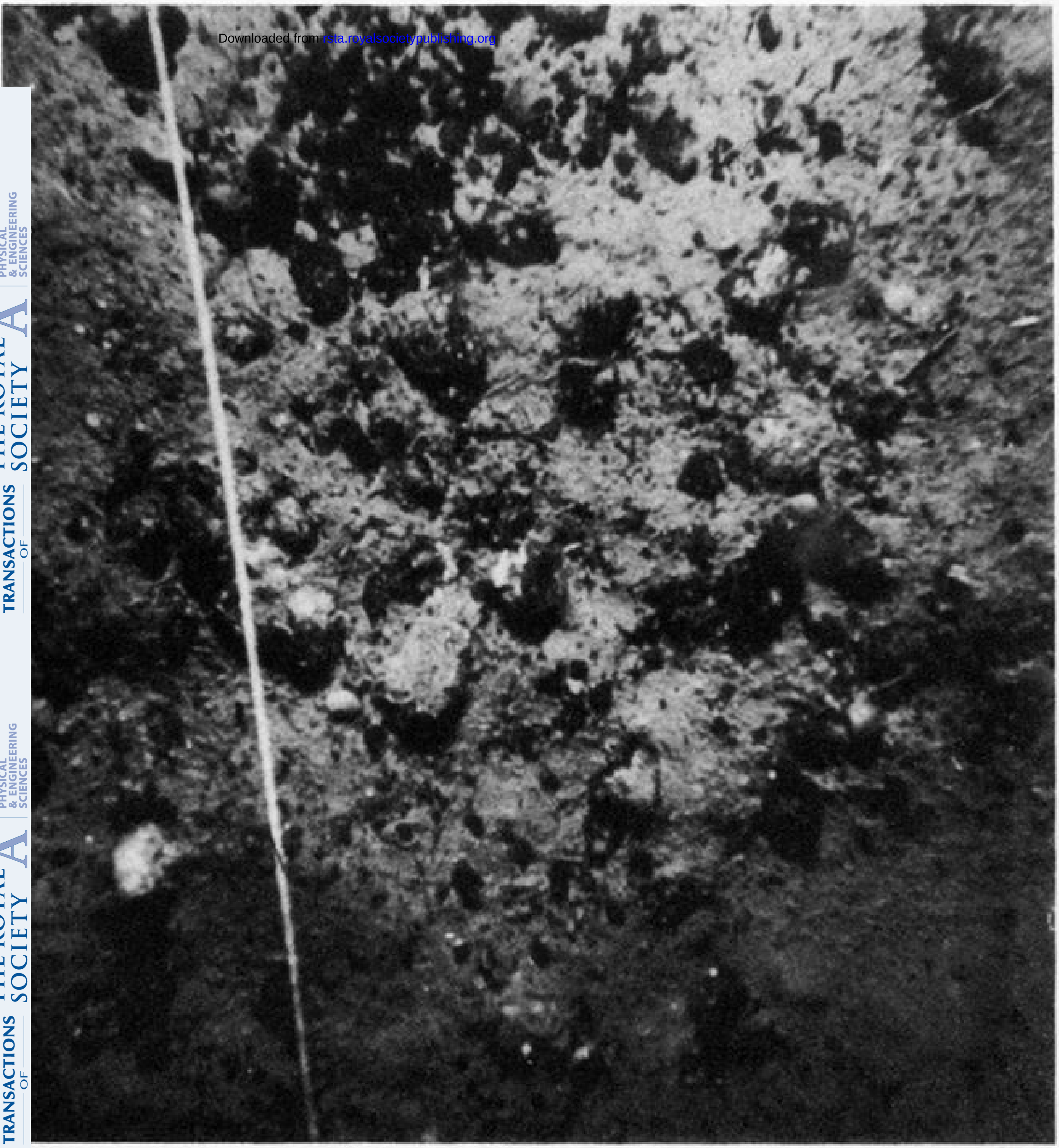


FIGURE 4. Phosphorite concretions offshore New Zealand.

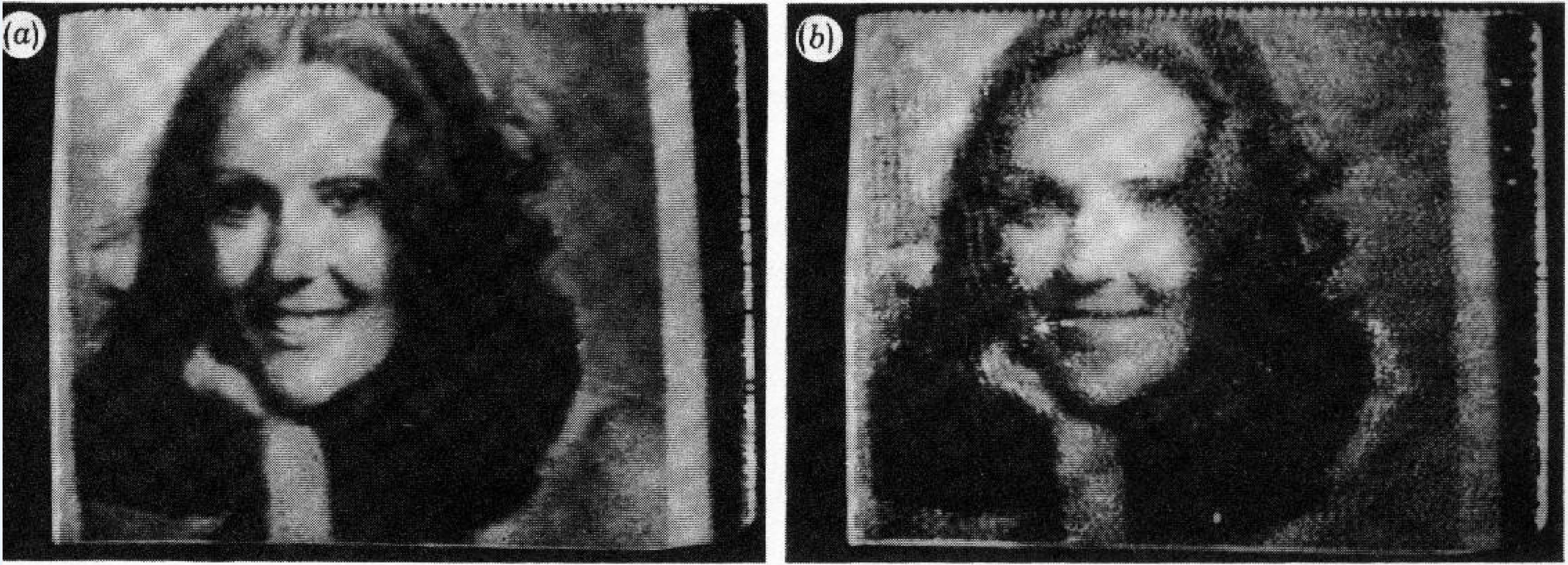


FIGURE 6. Television original (*a*) and image (*b*) after transmission through 2000 m of water (C.N.E.X.O.).

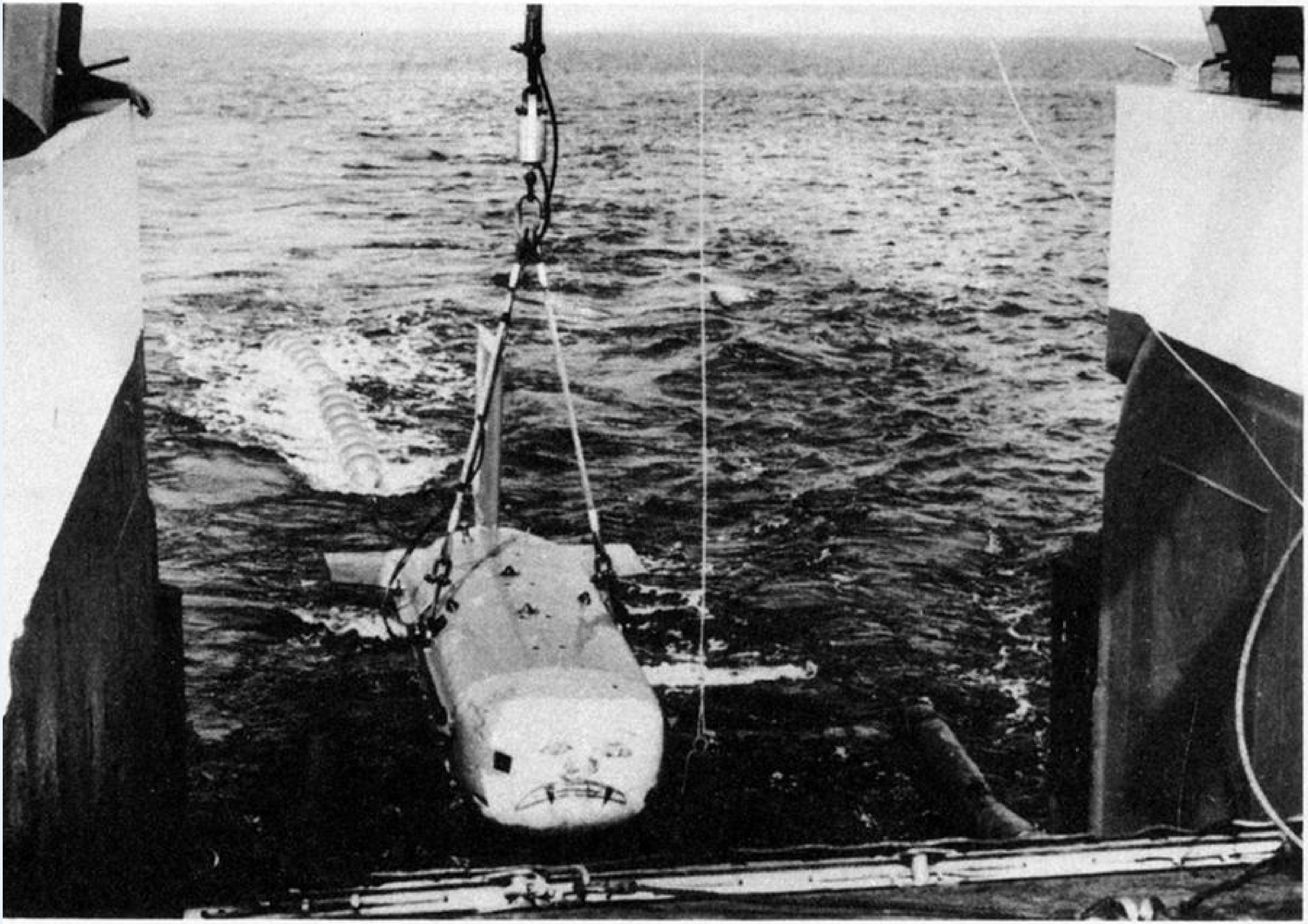


FIGURE 7. Deeptow, a cable guided observation fish.

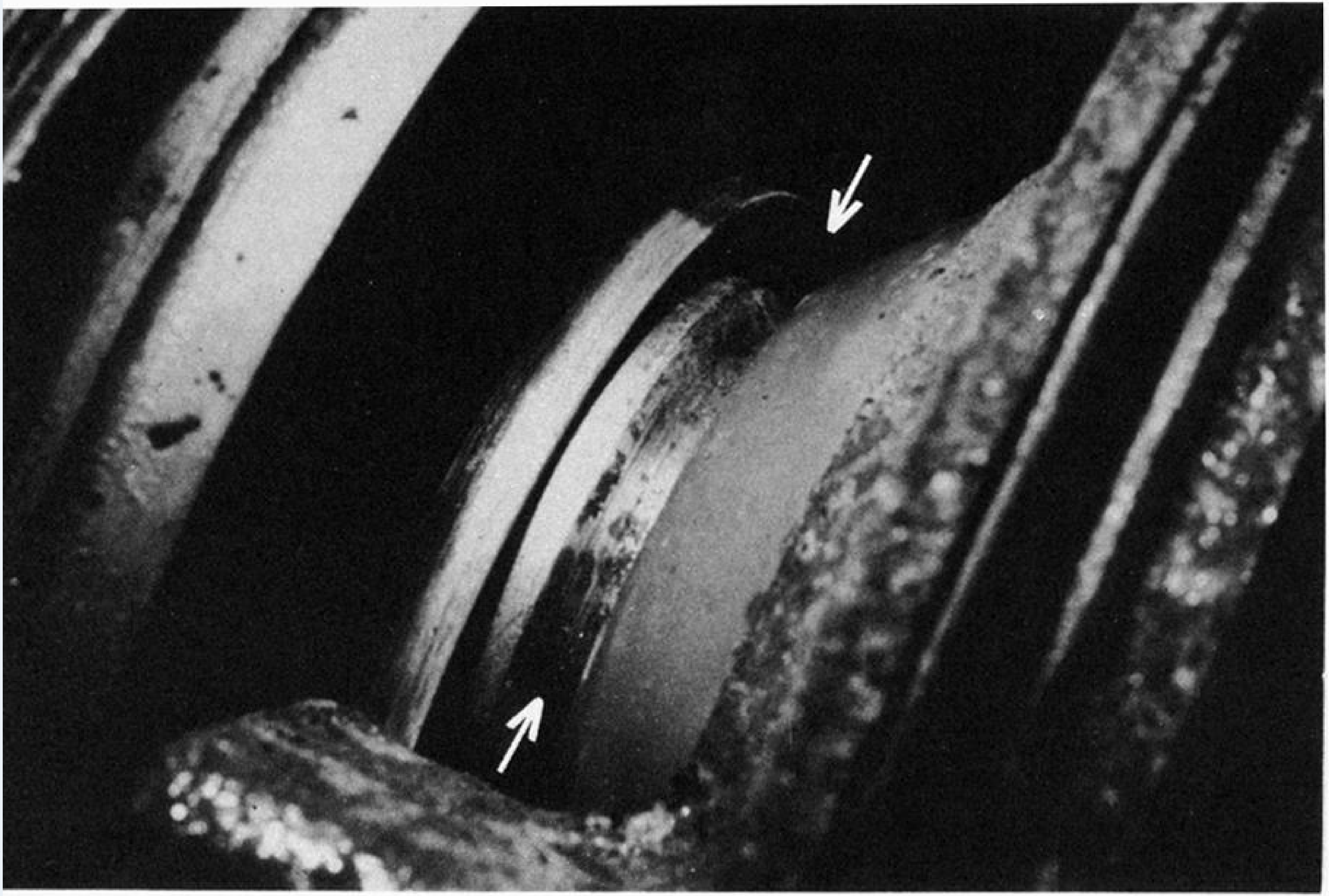


FIGURE 9. Erosion in an underwater slurry pump (Preussag/Worthington).

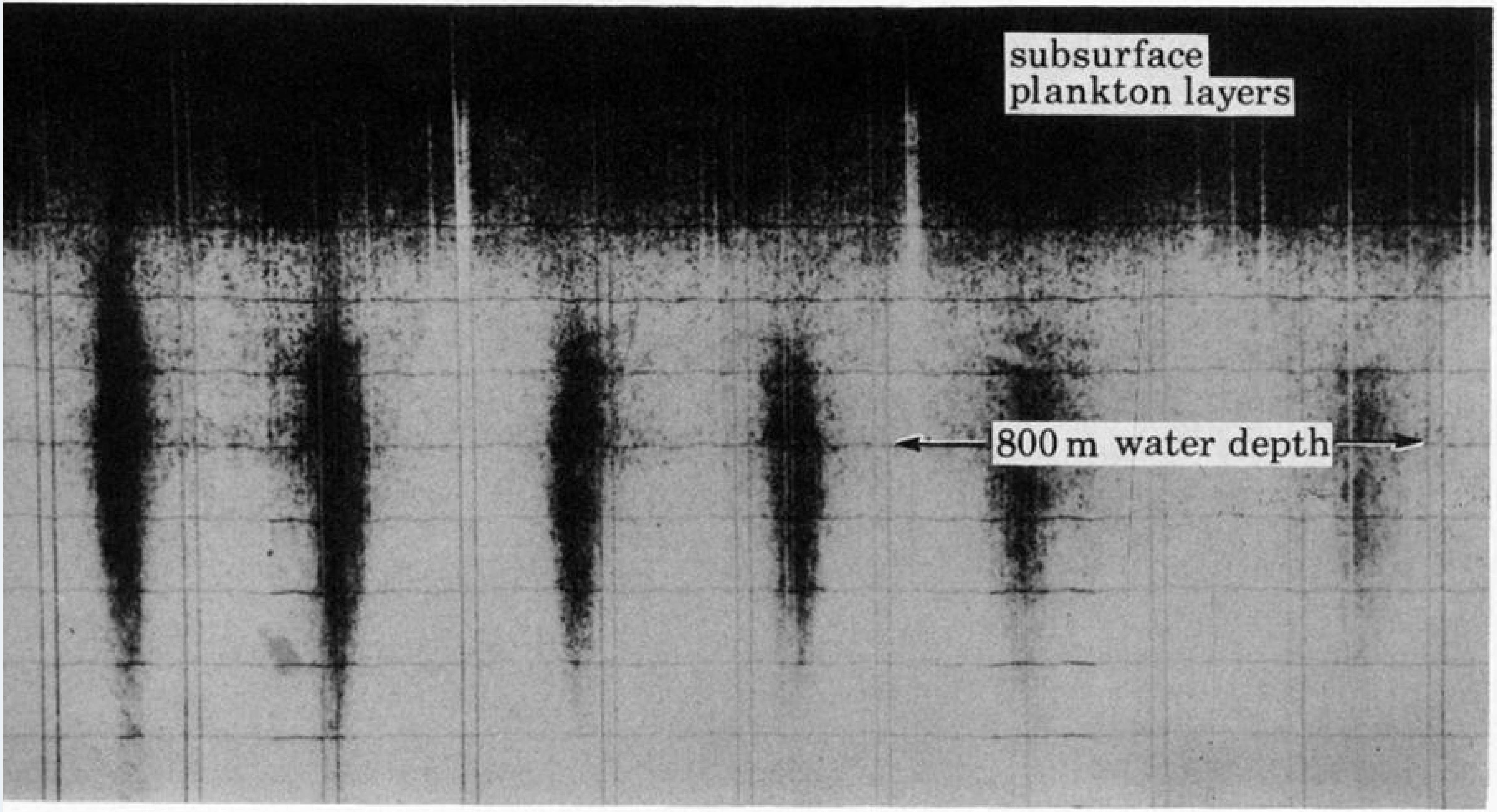
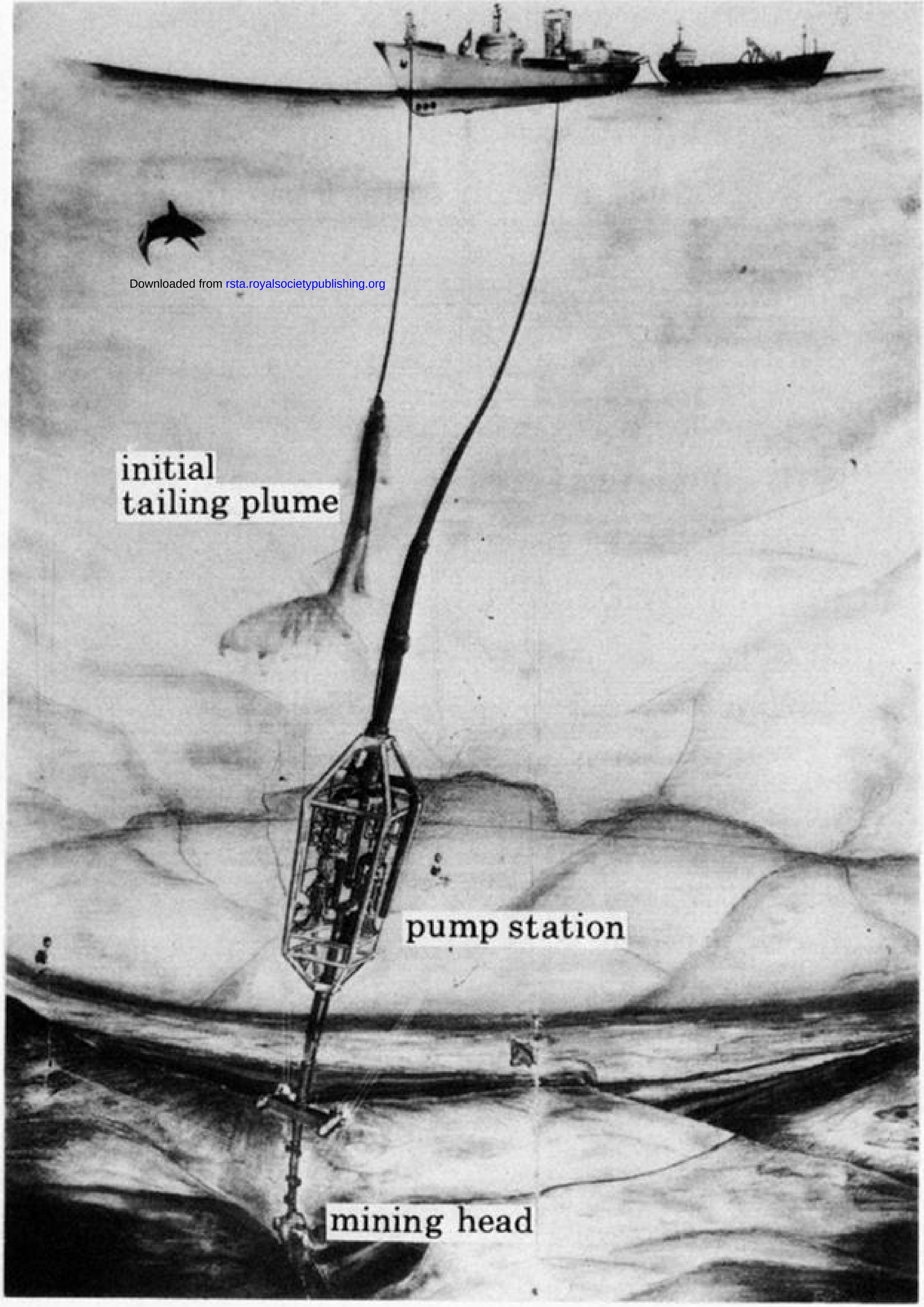


FIGURE 14. Tailing plume in the deeper Red Sea.



IGURE 15. Concept of the pilot mining operation in the Red Sea.