New Frontiers of Deep-sea Mineral Exploration and Mining* – *P.V. Sukumaran, Geological Survey of India, Mangalore (Email: pvs341950@gmail.com)*

A unique feature of our planet is the Ocean that covers ~71% of the Earth's surface. 60% of the ocean floor lies deeper than 2 km that remains relatively unexplored and what lies beneath this ocean is little known. However, even this little knowledge shows that the resources of the ocean floor are enormous. For instance, the manganese nodule resources of the ocean floor are estimated to stand at 500 billion tones! Scientific investigations during the last 30 years have resulted in discovering various types of mineral treasures on the seafloor that are only now becoming the focus of economic interest

Many countries have ventured into the sea with the aim of exploiting the newly discovered mineral resources that include not only the multi-element-enriched manganese nodules and encrustations, but also metalliferous sediments, placer minerals including diamonds, petroleum resources and the recently discovered seafloor massive sulphide (SMS) deposits and gas hydrates.

Gas hydrates or clathrates, discovered in recent years at the edge of continental slope and under permafrost Polar Regions, constitute a potential source of future energy. Gas hydrates are crystalline compounds that look like ice which occur when water molecules form a cage-like structure around smaller 'guest molecules'. The most common guest molecules are aliphatic hydrocarbons like methane, ethane, propane and butane but also nitrogen, carbon dioxide and hydrogen sulfide. But the most common guest molecule is methane and therefore gas hydrates are almost synonymous with methane hydrates. The oceanic reservoir of gas hydrates has been estimated to be about 10,000 to 11,000 GtC, though widely cited current estimates range from 500 to 63,400 GtC. Gas hydrates are said to have the energy potential equal to more than twice that of all fossil fuels combined and therefore oceanic clathrate reservoir is an mind-boggling resource. What is equally attractive about gas hydrates as a source of energy is their low carbon content which means less of carbon dioxide emission on combustion and thus they are a more environmental-friendly fuel. India has one

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of the richest methane hydrate deposits in the world discovered very recently in the Krishna-Godavari-Mahanadi offshore basins and in the Andaman Sea.

Polymetallic manganese nodules are of considerable economic interest for their metal contents like Cu, Ni, Zn and Co. However, owing to unresolved legal problems of mining in international waters interest in this resource has dwindled compared to what it was in the 1960s and 70s; and it is unlikely that manganese nodules will be mined in the near future. Current interest of researchers is directed to a new arena of the ocean floor, namely divergent and convergent plate boundaries and back arc basins not only for their scientific interest but also for the metal-rich sulphides being deposited in these environments by ocean-floor hydrothermal activity.

Characteristic of SMS Deposits

Besides constituting a new realm representing perhaps the limit for life hydrothermal vents are now known to house rich deposits of multi-element sulphide minerals called SMS deposits that add a new dimension not only to our understanding of the deep seafloor processes but also its economic bounty. Besides their scientific interest, ocean floor vents are being explored for pharmaceutical and biotechnological applications. The fact that many vent sites create massive polymetallic sulphide deposits has recently led to a resurgence of interest in mining them.

Most sites have been located in mid-ocean ridges at the East Pacific Rise, the Southeast Pacific Rise, the Northeast Pacific Rise, the convergent plate margins in Southwest Pacific and Mid-Atlantic Ridge; but only a few have been located at the ridge system of the Indian Ocean. Though hundreds of SMS sites have been discovered all along global spreading centres only a few have ore reserves of 10 million tonnes that is considered as economically viable to mine. They are modern analogs of giant volcanic-hosted massive sulphide (VMS) deposits being mined today on land such as the Kidd Creek deposit in Ontario, which formed in ancient oceans almost 3 Ga ago. However what appears mysterious is their size which is an order of magnitude smaller compared to VMS deposits on land. Perhaps we are still to discover such giant SMS deposits on the seafloor and many may also lie under thick cover of sediments deposited over them as plates moved away from the mid-ocean ridges. Among the four hundred-odd SMS deposits known to date, about 140 are of economic potential. The largest known SMS deposit is TAG (Trans-Atlantic Geotraverse) in the rift valley of the Mid-Atlantic Ridge which has about 10 million tones of ore.

SMS deposits contain significant concentrations of base metals like Cd, Pb and Cu as well as the precious metals Pt, Ag and Au; average metal contents are: Au: 0-20 gm/tonne, Ag: 0-1200 gm/tonne, Cu: 0-15 wt%, Zn: 0-5 wt%, Pb: 0-23 wt% and Fe: 5-50 wt%. The chief sulphide minerals in SMS deposits are pyrite, chalcopyrite, sphalerite and galena. The SMS deposits formed on calc-alkaline felsic lavas (andesite, dacite, rhyolite) in convergent boundary settings are relatively rich in Pb, Cu, Ba, Zn, As, Sb, Ag and Au unlike those formed on basaltic host rocks in Mid-ocean Ridges which is rich in Fe and Zn. Particularly interesting is the high concentrations of gold and silver in sulphide samples from back-arc spreading centres.

Formation of SMS Deposits

Seafloor Massive Sulphides get deposited at mid-ocean ridges, at ocean islands and seamounts, in the flanks of island arcs and at back-arc spreading centres. Most vents known to date are located at depths of 1500 to 3500 m, although a few occur in shallower waters. As cold oxygenated seawater penetrates downward into young fractured crust it becomes progressively warmer and undergoes a series of chemical exchange reactions with the host rocks. In the process of circulation oxygen and other relatively oxidized chemical species are consumed and the circulating fluids become anoxic as well as acidic, in the process acquiring numerous metals dissolved from the host rock. Eventually, the fluid is heated to such an extent that it cannot penetrate further due to buoyancy but begins to rise towards the seafloor. The rising fluid mixes with overlying cold oxygenated seawater, when the metal-rich sulphides are precipitated as chimneys of massive sulphides both at the sea floor (in the form of chimneys that rise 10s of metres) and in the underlying 'stockwork'. The ore bodies are made up of loose materials such as fallen chimneys, along with recrystallized sulphides. With passage of time the plates diverge from the Mid-ocean Ridges and venting activity eventually ceases. The magnitude of SMS deposits formed on vents depends on how long venting was active; those such as the TAG have been active for a 1,00,000 years and has given rise to considerably large deposits.

The Biology o Hydrothermal Vents

Deep hydrothermal vents, teeming with dense communities of exotic fauna, were first discovered in 1977 in the Galapagos spreading centre in the east Pacific Rise. Till then no body ever imagined that life can metabolise in an environment without oxygen and sunlight. Subsequent explorations of active vents around the world oceans confirmed that they constitute a remarkable and totally unknown eco-system where life is driven not by photo-synthesis but by chemosynthesis. Vent communities are supported by a food chain based on chemoautotrophic bacteria that oxidize H_2, H_2S and CH_4 emanating from vents to provide the energy for other vent symbionts.

Besides, the physicochemical environments at vent sites are extreme for life owing to steep chemical and temperature gradients (400°C, compared to 2°C for the surrounding deep ocean water). More than 500 species new to science have been discovered in the first 30 years of vent research. Endemic to vent ecosystems are animals specially adapted to life at the vents and are different from the fauna in the surrounding deep sea. Some of the key inhabitants associated with hydrothermal vents are tubeworms, bivalves, shrimps, gastropods and crabs. Our knowledge of vent fauna is just the tip of the iceberg and there is great potential for exciting discoveries in these environments. For instance, it was as recently as 2002 that a group of German researchers identified the most enigmatic and smallest organism (*Nanoarchaeum equitans*, 400 nm in size)

An active hydrothermal vent teeming with life

known to science from an active vent system off Iceland. Currently there is considerable gap in our knowledge of the diversities of biological communities inhabiting the active vents *vis-à-vis* the extinct ones. However, the diversity of life on inactive or extinct vents is much limited and obviously they are the ones mining companies are aiming at.

Exploration and Mining

Located at inaccessible areas of the seafloor, SMS deposits posed a great technological challenge for exploration until recently. This has been partly overcome with the world-wide availability of Remotely Operated Vehicles, Automated Underwater Vehicles (ROVs and AUVs) and research submarines which can be deployed on the seafloor and remotely controlled from mother vessels floating thousands of metres above. However, commercial interest in SMS deposits is restricted to those which lie within the EEZ of individual States. In this context the south-west Pacific seafloor has been an area of intense exploration activity in recent years, particularly by two multinational companies, namely Nautilus Minerals and Neptune Minerals. The southwestern Pacific floor is geologically very complex and tectonically very active with extensive zones of hydrothermal activity. Nautilus Minerals has recently investigated the Manus Basin of Bismarck Sea off Papua New Guinea for SMS deposits. They also have licenced considerable areas in waters off Papua New Guinea, Fiji, Tonga, the Solomon Islands and New Zealand.

Neptune Minerals has also been reportedly carrying out extensive exploration programmes in the western and south-western Pacific and have recently succeeded in discovering two extinct SMS fields in the Kermadec Arc region, off New Zealand. Nautilus Minerals is poised to bring their Solwara-1 site in the Territorial Waters of Papua New Guinea into full production in the current year. Pilot mining operations are planned for the end of 2010, followed by full-scale mining thereafter**.** This is a technology-driven field that requires innovations to work in extreme pressure-temperature environment and in highly rugged undersea terrains. But technological developments taking place are sure to overcome these barriers. Seafloor mining machineries called SMTs (Seafloor Mining Tools) which are gigantic crab-like mining robots are already in the field. We might soon see metals from the seafloor reaching the international markets by the turn of the decade that might even flood the market soon after.

Potential Environmental Impacts

Mining of SMS deposits is a new frontier that is bound to raise several unforeseen environmental problems. Mining in international waters is beset with legal tangles besides a maze of environmental problems threatening the marine biota. Active vents are more vulnerable because some members of vent organisms may perhaps become completely extinct as a consequence of mining; inactive vents may pose fewer problems. Lack of knowledge about species diversity, endemicity and migration habits of vent fauna is a major impediment in studying the environmental viability of SMS mining. Moreover no baseline data is yet available on which to predict the impacts of future mining. Nevertheless, it is heartening that both Nautilus Minerals and Neptune Minerals are currently supporting biological studies on vent habitats at their mining sites. Besides Neptune is reportedly undertaking detailed baseline assessments of their sites, which are extinct vents. The International Seabed Authority is also turning its attention to SMS deposits and is in the processes of finalising prospecting and mining regulations.