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## Economic potential of sea-floor massive sulphide deposits: ancient and modern

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# Economic potential of sea-floor massive sulphide deposits: ancient and modern

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Land-based massive sulphide deposits are of major importance to world mining and world commerce. Major products are base metals (copper, zinc, lead, tin), precious metals (gold, silver), and a number of special metals (e.g. indium, gallium, germanium). More than 100 modern analogues of massive sulphide deposits and hydrothermal systems are presently known at the modern sea-floor, including some very large accumulations of metals such as in the Atlantis II Deep in the Red Sea, at Middle Valley at the Juan de Fuca Ridge, and in the TAG deposit at the Mid-Atlantic Ridge. Currently, mining of hydrothermal deposits at the sea-floor appears to be most attractive for sites with (1) high gold and base metal grades, (2) site location close to land (i.e. within the Exclusive Economic Zone), (3) shallow water depth not significantly exceeding 2000 m (although the technology exists for mining in deeper water). The environmental impact will be minimal at those sites, which are inactive (i.e. not inhabited by vent fauna) and are not covered by sediments (no creation of sediment plumes due to mining activities). Some of the most prospective gold-rich deposits have been found in the territorial waters of Papua New Guinea. If drilling proves that mineralization extends to depth, these deposits may become the first marine mine sites for gold and base metal sulphide mineralization.

**Keywords:** sea-floor; massive sulphide; economic potential; gold; ancient VMS; modern VMS

## 1. Introduction

The discovery of black smokers, massive sulphides and vent biota at the crest of the East Pacific Rise at 21° N in 1979 (Francheteau *et al.* 1979; Spiess *et al.* 1980) confirmed that the formation of new oceanic crust by sea-floor spreading is intimately related to the formation of metallic mineral deposits at the sea-floor. It was documented that the 350 °C hydrothermal fluids discharging from the black smoker chimneys at this site in a water depth of *ca.* 2600 m continuously precipitate metal sulphides in response to mixing of the high-temperature hydrothermal fluids with ambient seawater. The metal sulphides including pyrite, sphalerite, and chalcopyrite eventually accumulate at and just below the sea-floor and have the potential to form a massive sulphide deposit. It has also been documented, that the circulation of seawater through the oceanic crust is the principal ore-forming process in this environment. Seawater that penetrates into the oceanic crust at sea-floor spreading centres is being converted to a hydrothermal fluid with low pH, low Eh, and high temperature during water–rock interaction above a high-level magma chamber. This fluid is then capable of leaching and transporting metals and other elements



Figure 1. Worldwide distribution of important land-based massive sulphide deposits and massive sulphide districts. VMS, volcanogenic massive sulphide deposits; SEDEX, sedimentary exhalative massive sulphide deposits.

which eventually precipitate as massive sulphides at the sea-floor or as stockwork and replacement sulphides in the sub-seafloor. The resulting sulphide deposits can reach considerable size. The TAG hydrothermal mound at the Mid-Atlantic Ridge at  $26^{\circ}$  N, for example, has a diameter of *ca.* 200 m, a height above sea-floor of *ca.* 50 m and is characterized by a black smoker complex, the top of which consists of several black smokers venting hydrothermal fluids at a temperature of more than  $360^{\circ}\text{C}$ . The energy output of the TAG system has been calculated to *ca.* 225 MW (Rona *et al.* 1993).

## 2. Ancient massive sulphide deposits

In the past, numerous studies have indicated that the hydrothermal systems and massive sulphide deposits at the sea-floor are the modern analogues of the ancient massive sulphide deposits in the geological record. This worldwide occurring class of ore deposits which is being mined for base metals (copper, zinc, lead, tin), precious metals (gold, silver) and a number of special metals (e.g. indium, gallium, germanium) is of major importance to world mining and world commerce. Figure 1 gives the location of major land-based massive sulphide deposits and massive sulphide districts worldwide including volcanogenic massive sulphides (VMS) and sedimentary exhalative massive sulphides (SEDEX) types. The first type, VMS, refers to massive sulphide deposits which are hosted by volcanic rocks; the second type, SEDEX, represents sulphide formation in sedimentary sequences which have accumulated in thermally active oceanic rift zones.

Important areas and districts with massive sulphide deposits are (1) the Noranda, Timmins and Bathurst camps in Canada, including the large Kidd Creek mine, (2) the Iberian Pyrite Belt in Spain and Portugal, including the Rio Tinto and Neves Corvo mines, (3) the Irish carbonate-hosted deposits Tynagh, Navan and Silvermines, (4) the polymetamorphic Scandinavian deposits, including the Boliden mine, (5) the

Table 1. Size and precious metal contents of VMS deposits (after Leistel *et al.* 1998)

| country        | size ( $10^6$ t) | Ag (t) | Au (t) |
|----------------|------------------|--------|--------|
| Australia      | 484              | 20 870 | 734    |
| Canada         | 1664             | 54 868 | 1964   |
| Spain/Portugal | 1765             | 46 188 | 887    |

Table 2. Top seven gold-rich VMS deposits (after Hannington *et al.* 1999)

|                      |          |
|----------------------|----------|
| Horne (Canada)       | 330 t Au |
| Flin Flon (Canada)   | 181 t Au |
| Bousquet (Canada)    | 163 t Au |
| Boliden (Sweden)     | 128 t Au |
| Quermont (Canada)    | 75 t Au  |
| Eskay Creek (Canada) | 71 t Au  |
| Rosebery (Australia) | 56 t Au  |

Rammelsberg and Meggen deposits in Germany, (6) the Urals deposits, including the Gai massive sulphides, (7) the Japanese Kuroko deposits, (8) the deposits on the mainland of Australia, including Broken Hill, Mt Isa and McArthur River, and (9) the Tasmanian massive sulphides in the Mt Read volcanic belt. The best examples of ophiolite-hosted massive sulphide deposits are found in the Troodos Complex on Cyprus and in the Semail Ophiolite in Oman.

On a worldwide scale, massive sulphide deposits contribute approximately 50% zinc, 40% lead, 15% copper as well as 40% silver and 5% gold to the world market. The Canadian deposits alone contain  $78.8 \times 10^6$  t combined copper, zinc, and lead metal ( $27.5 \times 10^6$  t copper,  $50.3 \times 10^6$  t zinc,  $1.0 \times 10^6$  t lead), which is almost similar to the metal content of the deposits in the Iberian Pyrite Belt ( $70 \times 10^6$  t copper + zinc + lead with  $18.0 \times 10^6$  t copper,  $38.6 \times 10^6$  t zinc, and  $13.6 \times 10^6$  t lead). The Australian deposits for comparison contain a total of  $5.7 \times 10^6$  t copper,  $18.9 \times 10^6$  t zinc, and  $6.6 \times 10^6$  t lead ( $31.2 \times 10^6$  t copper + zinc + lead; all data are from Leistel *et al.* (1998)).

The base metals (including tin) are the major commodities of massive sulphide deposits, but even so, gold and silver are economically important by-products of massive sulphide mining.

The Australian massive sulphide deposits have a combined size of  $484 \times 10^6$  t (including the deposits on the mainland of Australia and those in Tasmania) and contain a total of 20 870 t silver and 734 t gold (Leistel *et al.* 1998; table 1). The Spanish and Portuguese massive sulphide deposits in the Iberian Pyrite Belt have a total size of  $1765 \times 10^6$  t, which is the largest accumulation of massive sulphide ores on Earth. The total content of precious metals in the Iberian Pyrite Belt is 46.188 t silver and 887 t gold. By far the largest amount of silver and gold comes from the Canadian deposits ( $1664 \times 10^6$  t), which contain close to 55 000 t of silver and 2000 t of gold. Gold-rich VMS deposits account for approximately 10% of the current Canadian gold output (Robert 1990). Consequently, five out of the top seven VMS gold deposits worldwide are located in Canada, including the Horne mine (330 t gold), the Flin Flon deposit (181 t gold), and the Bousquet deposit (163 t gold; table 2).

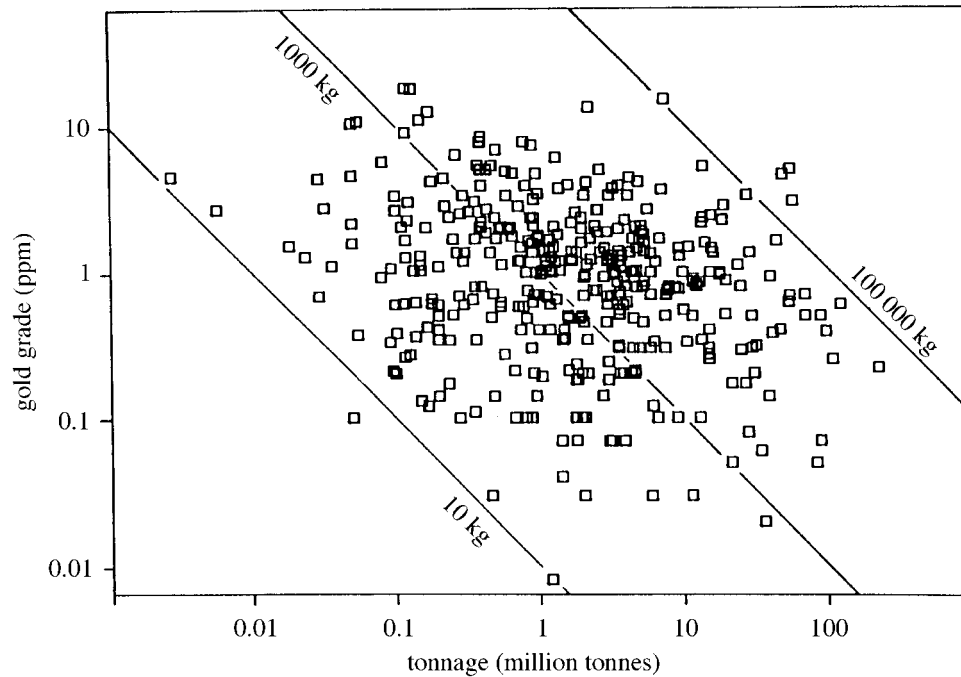


Figure 2. Gold grades versus tonnage for 372 land-based VMS deposits worldwide. Diagonal lines indicate quantities of contained gold (from Herzig & Hannington 1995b).

Figure 2 contains size and gold grade data for more than 350 VMS deposits worldwide and indicates that the average VMS deposit has a gold grade of *ca.* 1 ppm and a size of approximately  $5 \times 10^6$  t. Obviously, there are a large number of VMS deposits that are significantly larger than  $5 \times 10^6$  t and there is also a considerable number of deposits, that have gold grades which are distinctly higher than 1 ppm (up to more than 10 ppm gold).

In addition to the conventional base metals (zinc, lead, copper), some massive sulphide deposits have revealed high concentrations of gallium and germanium (SEDEX deposits) while others are rich in tin, such as the Neves Corvo mine in Portugal. The element indium is used for a number of high-technology applications, particularly in the computer industry. It is important to note that *ca.* 25% of the world indium production is coming from a single VMS deposit, which is the  $135 \times 10^6$  t Kidd Creek mine in Canada. However, it is known that the Neves Corvo deposit in Portugal also contains large amounts of indium and it can be expected that once the indium production from Neves Corvo ores has started, the respective mining company will immediately become the world's largest single indium producer.

### 3. Modern massive sulphide deposits

After about two decades of research, more than 100 sites of hydrothermal mineralization are known on the modern sea-floor (Rona & Scott 1993; Hannington *et al.* 1994). Figure 3 shows the location of the most important of those sites. The majority of sites are located on the East Pacific Rise, the Southeast Pacific Rise, and the Northeast Pacific Rise, mainly because the first discovery of an active high-

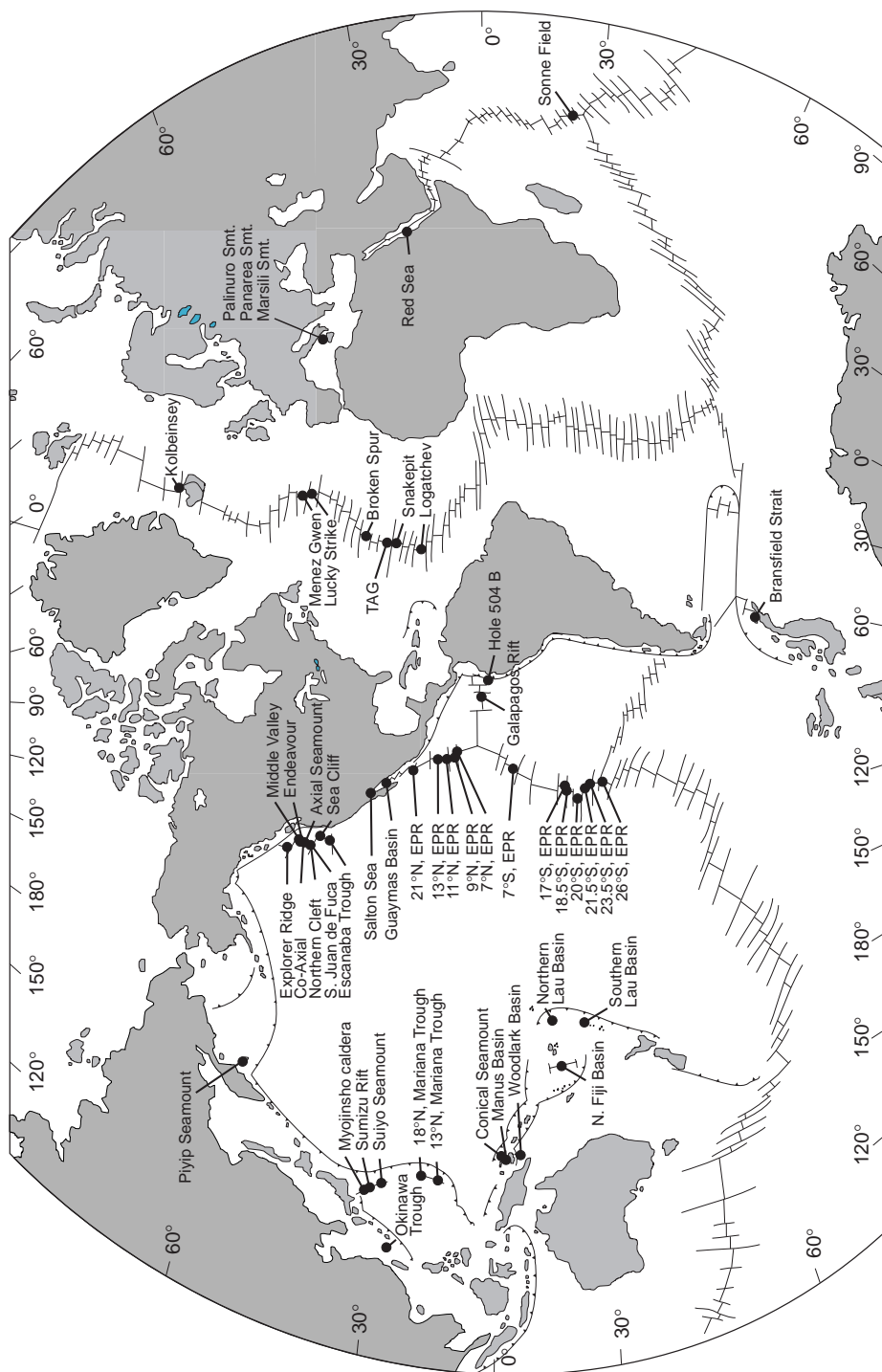


Figure 3. Location of hydrothermal systems and massive sulphide deposits at mid-ocean ridges and backarc spreading centres.

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Table 3. *Atlantis II Deep, Red Sea (after Mustafa et al. 1984)*

|              |                      |
|--------------|----------------------|
| area covered | 40 km <sup>2</sup>   |
| tonnage      | 94 × 10 <sup>6</sup> |
| wt% Zn       | 2.0                  |
| wt% Cu       | 0.5                  |
| ppm Ag       | 39                   |
| ppm Au       | 0.5                  |

temperature hydrothermal system was made at 21° N at the East Pacific Rise off shore Baja California. In recent years, a number of hydrothermal systems and associated sulphide deposits have been located on the Mid-Atlantic Ridge, including the large TAG hydrothermal mound at 26° N (Herzig *et al.* 1998). Only one site has so far been located on the ridge system of the Indian Ocean, close to the Rodriguez Triple Junction (Herzig & Plüger 1988; Plüger *et al.* 1990; Halbach *et al.* 1998). The scarcity of sulphide deposits on the Mid-Atlantic Ridge and in the Indian Ocean is, at least to a large extent, a function of restricted exploration activity in these areas.

In 1986, marine exploration moved into the island arc areas of the western Pacific and the first high-temperature hydrothermal vent sites were located at the active backarc spreading centre of the Manus Basin (Both *et al.* 1986). This was followed by the discovery of hydrothermal systems and massive sulphide deposits in the Mariana backarc (Craig *et al.* 1987; Kastner *et al.* 1987), the North Fiji backarc (Auzende *et al.* 1989), the Okinawa Trough (Halbach *et al.* 1989), and the Lau backarc (Fouquet *et al.* 1991). Massive sulphides from the Valu Fa Ridge in the Lau Basin were found to contain high concentrations of gold (up to 29 ppm) and the first examples of visible primary gold in polymetallic massive sulphides from the modern sea-floor (Herzig *et al.* 1993). Detailed geological, mineralogical, and geochemical analyses of the backarc deposits have indicated that these subduction-related sites represent the closest modern analogues of the majority of the economic land-based deposits which occur in felsic volcanic rocks instead of mid-ocean ridge basalts (Herzig & Hannington 1995a).

The largest known marine sulphide deposit is still the Atlantis II Deep in the Red Sea, which was discovered more than 10 years before the first black smoker at the East Pacific Rise (Degens & Ross 1969). The Atlantis II Deep mineralization largely consists of metalliferous muds, instead of massive sulphides, which is a consequence of the high salinity that the hydrothermal fluids acquire by circulation through thick Miocene evaporites on the flanks of the Red Sea Rift. A detailed evaluation of the 40 km<sup>2</sup> deposit has indicated 94 × 10<sup>6</sup> t of dry ore with 2.0% zinc, 0.5% copper, 39 ppm silver, and 0.5 ppm Au (Mustafa *et al.* 1984; table 3), which results in a total precious metal content of roughly 4 t of silver and 50 t of gold.

Other large deposits at the modern sea-floor include the Middle Valley deposit on the northern Juan de Fuca Ridge. This sediment-covered hydrothermal system has been drilled twice by the Ocean Drilling Program during Legs 139 and 169, and is estimated to contain *ca.* 8–9 × 10<sup>6</sup> t of sulphide ore (Zierenberg *et al.* 1998). During Legs 139 and 169, *ca.* 100 m of massive sulphides and 100 m of stockwork were drilled at the Bent Hill site. It was found that the stockwork zone is followed by a stratiform Cu-rich horizon ('deep copper zone') with copper grades ranging up to 17% Cu (Zierenberg *et al.* 1998). This significant discovery now represents an important

Table 4. Mining potential of sea-floor massive sulphide deposits

|  |
|--|
| high gold and base metal contents                                  |
| site location close to land (territorial waters of coastal states) |
| shallow water (ca. 2000 m water depth)                             |
| small environmental impact   |

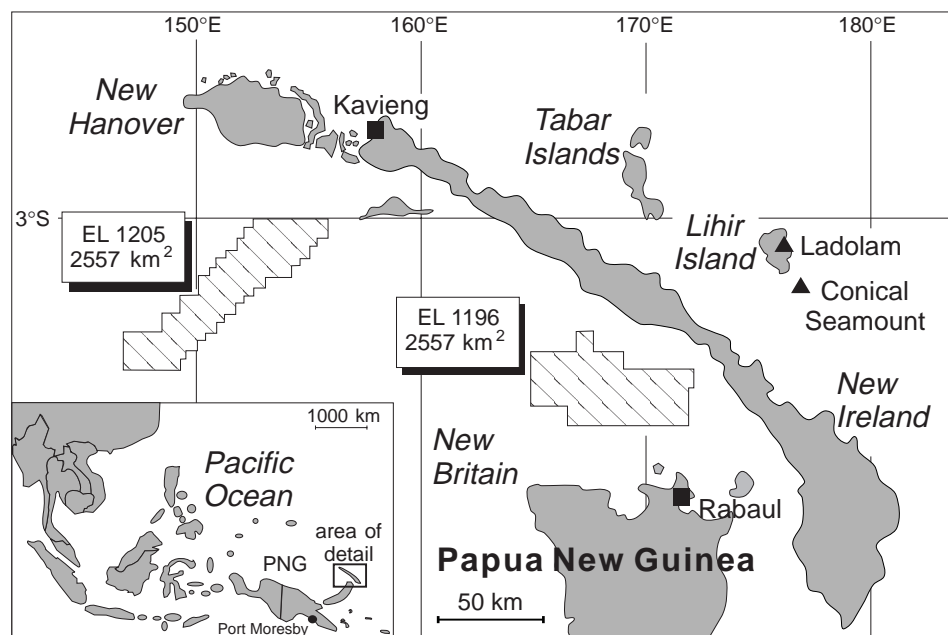


Figure 4. Map of the Manus backarc west of New Ireland showing the location of areas covered by an exploration licence granted to an Australia-based mining company by the Government of Papua New Guinea (after Broad 1997). Note the location of ‘Conical Seamount’ south of Lihir Island and the Ladolam gold deposit on Lihir Island.

new exploration target for the land-based mineral industry. The TAG hydrothermal mound located in 3650 m water depth on the Mid-Atlantic Ridge 26° N was drilled during ODP Leg 158 in 1994 to a total depth of 125 m (Humphris *et al.* 1995). It was estimated that the active TAG mound contains ca.  $2.7 \times 10^6$  t of sulphide ore above the sea-floor and approximately  $1.2 \times 10^6$  t of sulphides in the sub-seafloor stockwork (Hannington *et al.* 1998). A comparison of the size of the modern deposits with some of the ancient ore bodies and ore districts, indicates that extremely large deposits such as Kidd Creek in Canada ( $135 \times 10^6$  t) or Neves Corvo in Portugal ( $262 \times 10^6$  t) so far have not been discovered on the modern sea-floor.

#### 4. The mining potential of modern sea-floor deposits

For logistical reasons, it is unlikely that deposits such as TAG, Snakepit or Broken Spur, which are located in international waters on the Mid-Atlantic Ridge or the Sonne Hydrothermal Field at the remote Rodriguez Triple Junction in the Southern Indian Ocean, will become mining targets. This is also true for many of the sulphide



deposits along the East, Northeast and Southeast Pacific Rises. However, marine mining will be feasible under specific conditions ideally including (1) high gold and base metal grades, (2) site location close to land, i.e. within the territorial waters (200 nautical mile Exclusive Economic Zone or even 12 nautical mile zone) of a coastal state, (3) shallow water depth not significantly exceeding 2000 m (although the technology exists for mining in deeper water) (table 4). Under those circumstances, massive sulphide mining can be economically attractive. Sea-floor mining of massive sulphide deposits will only have a small environmental impact as the high density of the sulphide particles (*ca.*  $4 \text{ g cm}^{-3}$ ) will cause immediate redeposition of any sulphide debris produced by mining equipment such as large TV-controlled hydraulic grab systems. Sediment which could be disturbed by mining and possibly be transported by bottom currents would potentially create a major hazard to the marine ecosystem (cf. manganese nodule areas; Schneider & Thiel 1988). Amos *et al.* (1977) have pointed out that the greatest unknown and the greatest potential hazard with respect to manganese nodule mining is the behaviour and effect of sediment plumes at the sea-floor, within the water column, and at the surface. While the bottom water will be directly affected by sediment disturbance due to mining equipment, the impact on the water column and the surface will be due to discharge of sediments which have been lifted along with the manganese nodules. However, a significant sediment cover is commonly not present at most sea-floor VMS deposits and thus has not to be taken into account. Consequently, mining of selected sea-floor VMS deposits, in particular those that are inactive and not inhabited by any kind of vent fauna, does not create more environmental problems than the construction of a large harbour facility.

In December 1997, the Government of Papua New Guinea granted the first two marine exploration licences for sea-floor sulphide deposits to an Australia-based mining company (Broad 1997). The licences cover an area of *ca.*  $5000 \text{ km}^2$  in the Manus backarc basin and include the 'Vienna Woods' (Central Manus Basin) and the 'Pacmanus' (Eastern Manus Basin) sites, which are located on the east side of New Ireland (figure 4). The mineralizations occur at a water depth of 2500 m ('Vienna Woods') and 1450–1650 m ('Pacmanus'). Preliminary analyses of sulphides from the 'Vienna Woods' deposit indicate average gold contents of up to 30 ppm and maximum concentrations of more than 50 ppm (cf. Herzig *et al.* 1993). The average gold content of samples collected from the Pacmanus deposit is 15 ppm with a maximum of 55 ppm (Binns 1994). However, only a limited number of samples has been analysed so far and information about the depth extent of the mineralization is still lacking.

A recent discovery of gold mineralization in a modern forearc environment suggests that a number of previously unexplored settings on the sea-floor may be prospective for particularly gold-rich hydrothermal systems. The Tabar–Lihir–Tanga–Feni island chain, off Papua New Guinea, is host to a new class of marine mineral deposit, characterized by disseminated and stockwork-like sulphides in an alkaline volcano (Herzig & Hannington 1995*b*). The Tabar–Feni chain comprises a series of Pliocene to Recent volcanoes that occupy a forearc position in the New Ireland Basin on the west side of New Ireland (figure 5). Several of the volcanoes are still active and are host to several large porphyry stocks, active geothermal systems, and epithermal-style gold deposits, including the giant Ladolam gold deposit on the island of Lihir (minimum 600 t Au; Moyle *et al.* 1990), which is the world's largest epithermal gold deposit. Mining and processing operations at Ladolam started in 1997 (Lihir Gold Ltd 1998).

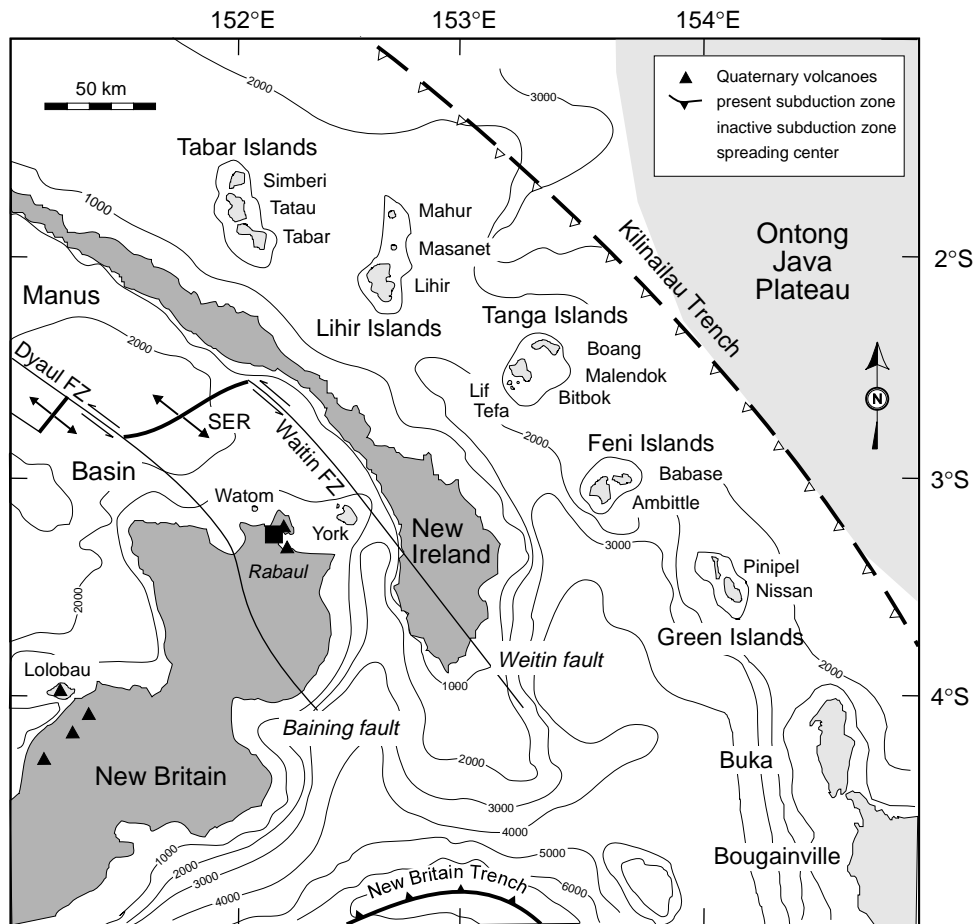


Figure 5. Map of the Manus backarc and New Ireland forearc system with the location of the Tabar–Feni island chain including the island of Lihir which is host to the giant Ladolam epithermal gold deposit.

Mapping of largely uncharted waters in the vicinity of Lihir revealed the position of several previously unknown volcanic cones *ca.* 10 km south of the island and 25 km south of the Ladolam gold deposit (Herzig *et al.* 1994; Herzig & Hannington 1995*b*; figure 6). From the crater of one of the volcanoes at a depth of only 1050 m ('Conical Seamount'), a large sample of trachybasalt locally mineralized with amorphous silica, pyrite, sphalerite, chalcopyrite, galena, unidentified Pb–As sulphosalts, and traces of anglesite and cerrusite was recovered. Bulk samples from the crater of 'Conical Seamount' contain up to 43 ppm gold (average 19 ppm) with grains of native gold (10  $\mu\text{m}$ ) identified as inclusions in pyrite and sphalerite. High concentrations of gold are uniformly associated with high concentrations of typical epithermal elements such as arsenic, antimony, and mercury, and associated with alunite, which is a typical alteration mineral known from the so-called high-sulphidation type of epithermal gold deposits on land. Similar to land-based epithermal gold deposits, the samples from 'Conical Seamount' have only low base metal contents (copper + zinc + lead < 3 wt%; Herzig & Hannington 1995*b*).

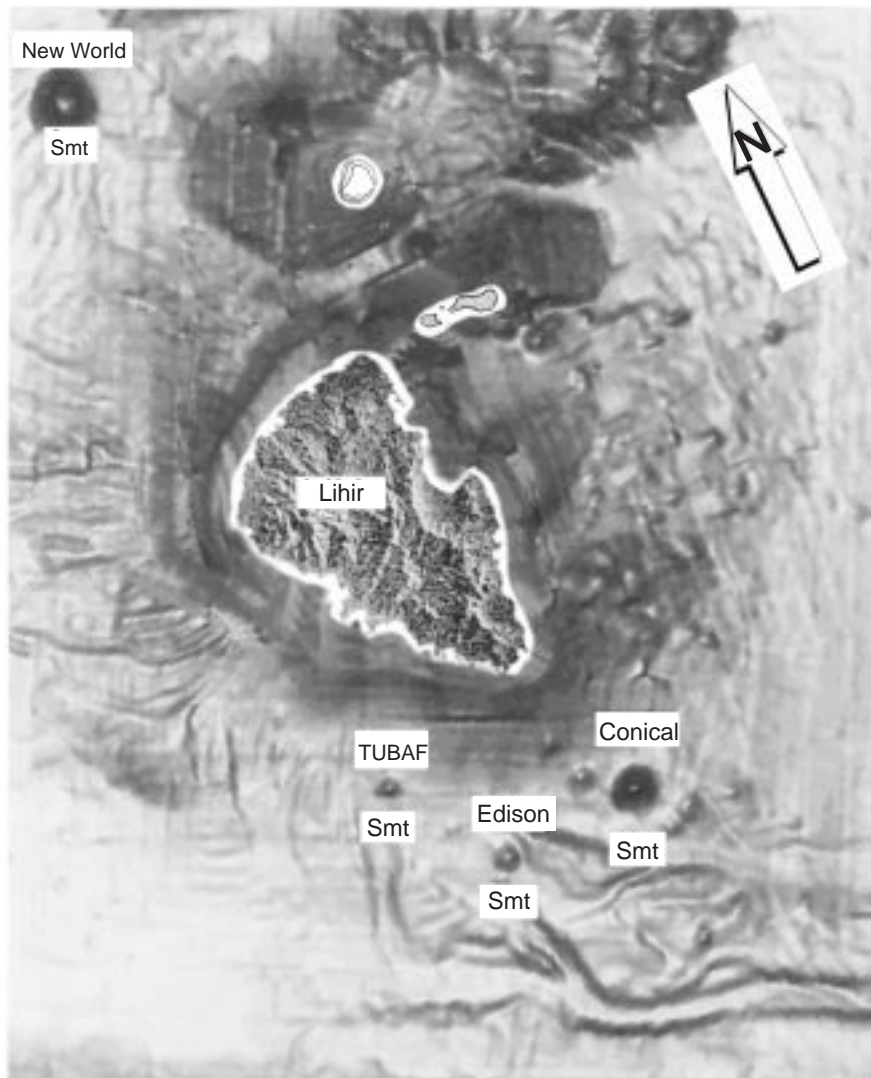


Figure 6. Bathymetry-based shaded relief of sea-floor topography of the submarine environment of Lihir Island showing the position of several volcanic cones north and south of Lihir. A gold mineralization has been found on 'Conical Seamount', which is located only *ca.* 10 km south of the island at a water depth of 1050 m. 'Conical Seamount' has the potential to become the first sea-floor gold deposit ever to be mined (cf. figure 4).

## 5. Perspective

The occurrence of hydrothermal activity in the rifted forearc region south of Lihir is the first documented evidence of sea-floor hydrothermal activity associated with alkaline volcanism and represents a new setting for hydrothermal activity not previously recognized on the modern sea-floor. The discovery of high gold contents associated with amorphous silica and alunite in hydrothermal precipitates at 'Con-

Table 5. Characteristics of the 'Conical Seamount' deposit off shore Papua New Guinea

|  |
|--|
| up to 43 ppm Au                          |
| water depth 1050 m                       |
| 10 km south of Lihir Island              |
| territorial waters of Papua New Guinea   |
| direct access to gold-ore dressing plant |

ical Seamount' may be the first true example of a shallow-marine epithermal system, analogous to gold-producing deposits on adjacent volcanic islands. If further exploration and drilling prove that high-grade gold mineralization is widespread and abundant, 'Conical Seamount' may become the first marine gold deposit to be mined. In addition to high concentrations of gold, the advantages of this site include shallow water depth (1050 m) and the location within the 12 nautical mile zone of Papua New Guinea. Processing of the gold ore could take place in the 10 km distant Ladolam gold processing plant on Lihir (table 5). If these developments become reality in the near future, they will have very significant implications for the further development of sea-floor mining. About 35 years after the oil industry went offshore, the mineral industry may follow.

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*Discussion*

R. HOLROYD (*Tunbridge Wells, UK*). I knew of the existence of these sorts of deposits, but Professor Herzig didn't describe how they are exploited. Is it by drop grabs? How are the deposits actually going to be mined because at 2000 or 3000 m it is not quite so easy as it sounds?

P. M. HERZIG. The deposits are mined the same way that we do exploratory or scientific investigations, which is to use a TV-guided grab system. We have several large grabs, which can hold *ca.* 3 t; they have a TV camera in the centre and lights around and they can be used to a depth of 5000 m. We can actually select the sample and can grab it and can even open the grab to get a new sample if we want to. But I think the limit for mining should be around 1000–2000 m. I don't think that anybody would consider mining sulphide deposits at the sea-floor in 3000 or 4000 m depth.

R. HARDMAN (*Amerada Hess Ltd, London, UK*). I am surprised that 3 ppm is considered possibly economic.

P. M. HERZIG. Well, the maximum values in the Manus Basin and Conical Seamount deposits are 55 ppm and 43 ppm, respectively. What we now need is more samples in order to obtain a true average value.

R. HARDMAN. I got the feeling that the ores were much richer in the ancient deposits than in the modern ones. What determines the mineralization, because again there were very different values in some of these deposits?

P. M. HERZIG. I think one big problem when looking at the sea-floor massive sulphide deposits from which we have samples so far is that those samples are from the surface. They were collected by submersibles or by dredges and we don't have much information about depth. Some information is available from the Middle Valley deposit where ODP drilled and some depth information is available from the TAG mound where we drilled with ODP in 1994. One of the results of the TAG drilling was that the upper 3–5 m are extremely rich in copper, zinc and gold and a number of other trace metals, and that after we had passed this zone we encountered pyrite, anhydrite and quartz and basically nothing else. Thus at TAG we are looking at a pyrite mound which has a very thin skin of chalcopyrite, sphalerite and gold-bearing pyrite. We think this is due to a process which is called 'zone refining', whereby hydrothermal fluids continuously circulate through the mound and pick up the metals—they have the right chemistry to do that—and the metals are being redeposited at the sulphide–seawater interface. In answer to the second part of your question, it is the source rocks that control the fundamental mineralogy and geochemistry. There is a considerable difference between the mineralogy and the chemical composition of sulphides in the backarcs of the Southwest Pacific and sulphides at the mid-ocean ridges. At the mid-ocean ridges we are dealing with mid-ocean ridge basalts and in the Southwest Pacific we are dealing with intermediate to felsic volcanics, in some cases even rhyolites. The rhyolites have higher concentrations of lead, antimony, arsenic and other elements such as zinc and they provide the

first-order control on the composition of the deposits. Gold is a different story; the initial gold content of rhyolite is *ca.* 1 ppb and the primary gold content of mid-ocean ridge basalts is also on the order of 1 ppb.

An idea that we published on this some time ago is that the felsic rocks create a specific chemistry of the hydrothermal fluids—they have a lower buffer capacity and a higher oxidation potential—which means that they can leach the 1 ppb gold in the source rock more effectively, maybe on the order of 95% of the gold, while the hydrothermal fluids in the mid-ocean ridge areas can leach only perhaps 45 or 50%. So in the case of gold, it's not the source rock composition which controls the enrichment of the ore at the sea-floor, as for other elements, but it is the fluid chemistry that is influenced by the source rocks.

M. OSMASTON (*Woking, UK*). Professor Herzig didn't mention in his listing of deposits those of the Norseman–Wiluna belt, in the Yilgarn Craton, Western Australia. Was that because he regards them as different? I agree that most of them are nickel.

P. M. HERZIG. There are some massive sulphide deposits which are in between a VMS deposit and an epithermal deposit so they are transitional. For my map I just used deposits where I have got good data on the chemical composition and the mineralogy of the ores.

J. A. KARSON (*Duke University, North Carolina, USA*). What are the constraints on how long it takes these various ore bodies to form? Could Professor Herzig also comment about the heat source?

P. M. HERZIG. Now, as you may know, the TAG mound has been dated and the first low-temperature hydrothermal activity producing manganese and iron oxides started about 140 000 years ago. However, the high-temperature hydrothermal activity at TAG started 25 000 years ago according to dating of submersible samples. Claude Lalou, who has done the dating on the TAG material, has indicated in her papers and in her discussions that there are periods of high-temperature activity every 5000–6000 years. Thus, there was not a continuous formation of sulphides as can be seen from the two terraces which we have at the TAG mound. The periodicity may be due to the replenishment of the magma chamber every few thousand years. This, however, creates a problem with the big deposits, like Kidd Creek, where the heat source must have been available for *ca.* 6 Ma. This may have something to do with the primitive nature of the Archaean crust.

R. S. WHITE (*Bullard Laboratories, University of Cambridge, UK*). On the East Pacific Rise individual hydrothermal systems are active for probably only one hundred or a few hundred years at a time. Is that sufficient time to build an economic deposit? Or is it necessary for hydrothermal activity to keep recurring at the same location in order to build an economic deposit? How many economic sulphide deposits do you think there may be along slow or fast spreading ridges?

P. M. HERZIG. Personally, I don't think that the deposits at the mid-ocean ridge will ever be economic because they don't fulfil the requirements I mentioned. In particular, the metal content is not attractive enough because those deposits usually tend to be poor in gold. Regarding how long it takes to form an economic deposit I think that TAG again is a good example. It took at least 25 000 years to make

a deposit which has *ca.*  $4 \times 10^6$  t, is *ca.* 200 m in diameter and 50 m high and has a considerable stockwork zone, although I do not consider TAG to be economic, as I pointed out before. Many of the dots on my map are only small systems on the mid-ocean ridges which have been active for a few hundred years and some of them are extinct but may start activity again.

K. ROHR (*Stable Geophysics, North Saanich, British Columbia, Canada*). Professor Herzig stated a depth beyond which mining is not feasible, yet the territory leased for underwater exploration lies deeper than your limit. Could he explain the criteria for his limit and why people would be exploring below that? Although it lies below his limit for feasibility, does he think that Middle Valley of the Juan de Fuca Ridge could be economically viable?

P. M. HERZIG. That is an interesting question. Middle Valley is within the Exclusive Economic Zone of Canada and before ODP started drilling the Canadians required an environmental impact study. The Middle Valley is estimated to contain *ca.*  $8-10 \times 10^6$  t of sulphide, at a conservative estimate, according to a recent publication in *Nature*, and I know that Canadian companies have been thinking about the possibility of mining there. However, I think that the big companies are still waiting to see what's going to happen in this field and that it will require adventurous companies to get into sea-floor mining now in restricted small areas like the Manus backarc or the New Ireland forearc, where gold-rich mineralization occurs between 1000 and 2500 m depth.

K. ROHR. One point I wanted to bring out about the Juan de Fuca Ridge is that the largest vents and the biggest deposits on the Endeavour, Middle Valley and Explorer segments are in regions of high seismicity and that it appears to me that a broad seismic belt is associated with the relocation of the triple junction. Thus, I think widespread faulting is promoting the hydrothermal circulation in these segments that is different from, say, along the rest of the Juan de Fuca Ridge.



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