International Ridge-Crest Research: **Back Arc Basins**

Petrology, Gold Mineralization and Biological Communities at Shallow Submarine Volcanoes of the New Ireland Fore-Arc (Papua-New Guinea): Preliminary Results of *R/V Sonne* Cruise SO-133

P.M. Herzig[1], M. D. Hannington[2], P. Stoffers[3] and the shipboard scientific party (K.-P. Becker[1], M. Drischel[1], J. Franklin[2], L. Franz[1], J. B. Gemmell[4], B. Hoeppner[1], C. Horn[5], K. Horz[2], T. Jellineck[6], I. R. Jonasson[2], P. Kia[7], S. Nickelsen[1], J. Percival[2], M. Perfit[8], S. Petersen[1], M. Schmidt[1], T. Seifert[1], O. Thießen[3], M. Türkay[6], V. Tunnicliffe[9], and K. Winn[3])

[1]*Department of Economic Geology, Freiberg University of Mining and Technology, Brennhausgasse 14, D-09596 Freiberg, Germany*
[2]*Geological Survey of Canada, 601 Booth Street, Ottawa, ON K1A 0E8, Canada*
[3]*Institute of Geoscience, University of Kiel, Olshausenstrasse 40-60, D-24118 Kiel, Germany*
[4]*CODES, University of Tasmania, GPO Box 252-79 Hobart, Tasmania 7001, Australia*
[5]*Department of Microbiology, University of Regensburg, Universitätsstr. 31, D-93053 Regensburg, Germany*
[6]*Forschungsinstitut und Naturkundemuseum Senckenberg, Senckenberganlage 25, D-60325 Frankfurt/Main, Germany*
[7]*Geological Survey of Papua New Guinea, Department of Mineral Resources, Private Mail Bag, Port Moresby, N.C.D., Papua New Guinea*
[8]*Department of Geology, 1112 Turlington Hall, University of Florida, Gainesville, FL 32611, USA*
[9]*Department of Biology, University of Victoria, Box 3020, Victoria, BC V8W 3N5, Canada*

Introduction

Cruise SO-133 of *RV Sonne* conducted detailed mapping and sampling in a zone of recent seismic and volcanic activity and elevated heat flow south of Lihir Island, Papua New Guinea between Jul. 20-Aug. 3, 1998. This cruise was a follow-up program of a reconnaissance survey (SO-94) conducted in 1994, which originally mapped the areas surrounding the Tabar-Lihir-Tanga-Feni island chain (TLTF) to the east of New Ireland (Herzig et al., 1994; Herzig and Becker, 1996). Cruise SO-133 confirmed the occurrence of epithermal style gold mineralization originally discovered at 'Conical Seamount' during cruise SO-94 (Herzig and Hannington, 1995). Conical Seamount is located only about 10 km south of Lihir Island, which is host to the giant (40 million ounces) Ladolam epithermal gold deposit (Moyle et al., 1990). The objectives of cruise SO-133 were to establish the nature and extent of volcanism, hydrothermal activity, and biological communities associated with active extension of the old fore-arc crust of the New Ireland Basin in the vicinity of Lihir Island (Fig. 1) and to further investigate the epithermal gold mineralization at Conical Seamount.

Geological Setting

The Tabar-Feni island chain is located in a fore-arc basin behind the presently inactive Manus-Kilinailau

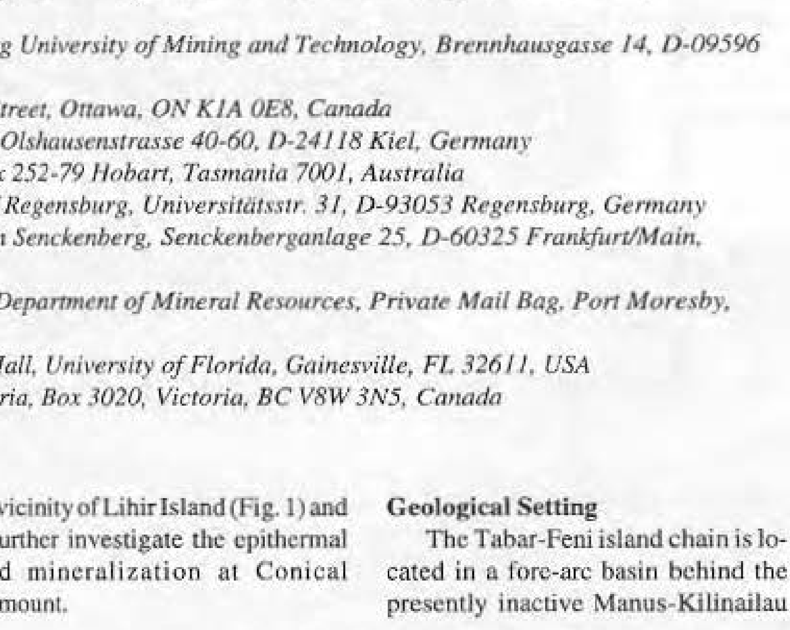

Figure 1. Regional tectonic map showing the location of the New Ireland Basin and the Tabar-Lihir-Tanga-Feni island chain. Box indicates study area of cruise SO-133.

trench northeast of Papua New Guinea.Volcanic activity on the islands, which began about 3.5 Ma ago, appears to be related to extension along northeast-trending structures that cut across the New Ireland Basin (Stewart and Sandy, 1988; McInnes and Cameron, 1994). Since Pliocene-Pleistocene time, partial melts associated with extension in the thickened crust of the New Ireland Basin have risen through the old fore-arc crust along reactivated faults to form the volcanic islands of the Tabar-Feni chain. These structures are thought to be related to regional plate rotation (Exon et al., 1986; Stewart and Sandy, 1988; McInnes,1992). Although plate rotation has isolated the Tabar-Feni chain from the presently active arc of New Britain, the present volcanism on the islands is most likely related to subduction from the south along the New Britain-Solomon trench.

A conjugate set of NE-NW striking faults that control the volcanism on the islands has been documented in Landsat and airborne magnetics surveys, and similar structures have been identified in the offshore areas (Gulf Research and Development, 1973; Exon et al., 1986). The Lihir island group itself is situated on a large uplifted block, raised by regional southward compression along the Manus-Kilinailau trench. During the late Miocene, nearly 7 km of sediment accumulated in the basin on top of Eocene to early Miocene volcanic basement.

Records of seismic activity between the Lihir group and New Ireland show that shallow earthquake epicenters are confined to a distinctive NE-SW corridor along the axis of the Lihir group (Port Moresby Geophysical Observatory, 1994). The earthquakes define a narrow seismic zone, and the recent tectonic activity along this corridor may be an indication of the beginning of the break up of New Ireland in response to the present subduction of the Solomon Plate and back-arc spreading in the Manus Basin. New Ireland is already noticeably thinned along the portion of the island immediately opposite Lihir.

The few radiometric dates available indicate that the most recent volcanic eruptions on Lihir occurred at about 1.1 Ma (Johnson et al., 1976). The most recent eruption in the island chain was dated at 2,300 years ago at Feni to the extreme southeast (Licence et al., 1987). These eruptions covered wide areas with volcanic ash, ranging from 5 to 30 cm in thickness, some of which was recovered in sediment stations during SO-133. The discovery of even younger volcanic cones in the area south of Lihir implies that volcanism in the New Ireland Basin is now focussed in the active tectonic zone of the Lihir group.

Cruise Objectives

The main focus of cruise SO-133 was the detailed investigation of several young volcanic cones discovered during SO-94 (including Edison Seamount, TUBAF Seamount, and Conical Seamount, Fig. 2) and nearby fault zones associated with the uplift of the pedestal of Lihir.

Specific objectives of the cruise included:

(1) to establish the extent of recent volcanism and extension south of Lihir by investigating all bathymetric anomalies, including major boundary faults and possible volcanic cones, initially mapped during SO-94.
(2) to determine the extent and character of alteration and epithermal gold mineralization at Conical Seamount.
(3) to establish the present status and extent of hydrothermal venting at Edison Seamount, and to document and sample representative suites of vent specific fauna, including smaller and rarer species and meiobenthos.
(4) to determine the source of near-bottom CH_4 anomalies south of Lihir.
(5) to characterize the history of eruptions, and to evaluate the diversity of xenoliths occurring in the alkaline mafic volcanics at TUBAF Seamount.
(6) to sample the recent record of subaerial volcanic activity in deep sediments along the northwest part of the New Ireland Basin.

Principal Results

Petrology

Twelve separate volcanic cones have now been mapped and sampled in the area (Fig. 2), and a preliminary assessment of their age progression implies several episodes of volcanism. Five of the cones have well-defined summit craters, up to several hundred meters in diameter and up to 50 m deep. Volcanic rocks are exposed at the summit of four of the cones, and the remaining volcanoes are heavily sedimented (up to 5-10 m thickness of sediment in the summit craters). The variable sediment thickness implies that volcanic activity in the area has likely been episodic for at least the past 100,000 years. A major swarm of volcanic eruptions during this time would coincide with the age of recent intrusive activity and associated geothermal systems on Lihir.

The volcanic rocks recovered from Edison, Conical, and TUBAF seamounts consist of highly alkaline, SiO_2-undersaturated pyroxene-phyric alkali-olivine basalt and trachybasalt, with locally abundant phenocrysts of pyroxene, magnetite, and phlogopite. The ejecta blanket at TUBAF Seamount comprises mainly fresh, sand-sized ash, lapilli, and small rounded bombs (up to 10 cm). The absence of any pelagic sediment covering the pyroclastic deposits suggests that the last eruption of this cone was very recent. By comparison, the sediment within the crater at Edison is at least several meters deep, suggesting that the volcano has been dormant for thousands of years (sedimentation rates are approximately 5 cm/1000 yr). Nevertheless, Edison Seamount shows a similar eruptive style to TUBAF Seamount, which is much younger. An extensive suite of samples from TUBAF Seamount provides a detailed cross-section of the old New Ireland Basin fore-arc crust, as recorded in xenoliths recovered from the volcanic ash. These xenoliths include a full suite of lithologies from mantle nodules (dunite, peridotite, pyroxenite, wherlite), through

International Ridge-Crest Research: **Back Arc Basins:** Herzig et al. continued...

gabbroic material and plagiogranite, to metasedimentary rocks. Additional sampling at Edison Seamount revealed that this older volcano also contains abundant xenoliths. Distinctive peperitic textures were also found in the samples from Edison Seamount, indicating eruption of the basalt into wet pelagic sediments. Most of the smaller volcanoes in this area with well-defined summit craters appear to be pyroclastic cones, composed of volcanic ejecta blown from the small pit craters.

Alteration and Mineralization

A comprehensive TV-grab sampling program at the summit of Conical Seamount recovered distinctive polymetallic (Zn+Cu+Pb+As+Sb+Ag), epithermal-style vein mineralization and pyritic stockwork material with locally intense clay-silica alteration. The mineralization consists of clay minerals, pyrite, and polymetallic sulfides including pale yellow sphalerite, disseminated galena, minor chalcopyrite, sulfosalts, and As-sulfides (realgar, orpiment). The top of the deposit, in the clay-silica zone, is deeply altered, and the basalt is completely replaced by illite+smectite+chlorite, some kaolinite, K-feldspar and silica. The original pyroxene phenocrysts in these rocks are pseudomorphed by white clay minerals, and most of the primary magnetite has been destroyed. The intense clay-silica alteration grades outward into weakly altered basalt breccias that are veined by pyrite. The weaker alteration is closely associated with fine-grained disseminated pyrite. Camera surveys across several hundred meters of the top of Conical Seamount revealed widespread but discontinuous patches of stained sediment, suggesting that low-temperature, diffuse hydrothermal vents were formerly active near the summit of the volcano. Fe-oxyhydroxide staining is exposed over a strike length of at least 250 m, and dredging of the flanks of the volcano also recovered intensely altered lavas with weak mineralization and thick Fe-oxide crusts. The abundance of Fe-oxide gossan implies that the hydrothermal system is now extinct and that the mineraliztion is rather old. The most striking feature of the mineralization is the elevated concentration of Pb, Zn, Cu, As, Sb, and Ag, which resembles typical polymetallic vein mineralization in subaerial low-sulfidation epithermal systems (Hedenquist and Lowenstern, 1994).

Shipboard analyses of the sulfide-rich material contained an average of 0.8 wt.% Zn, 0.3 wt.% Pb, 0.04 wt.% Cu, 3400 ppm As, 160 ppm Sb, 36 ppm Ag, and 9.3 wt.% S based on 25 samples and 10 gram assays. The most intensely mineralized material contains up to 4.5 wt.% Zn, 2.0 wt.% Pb, 2.0 wt.% Cu, 2.6 wt.% As, 1950 ppm Sb, and 38.0 wt.% S. Shipboard gold analyses (ASV) of these samples have indicated gold concentrations of up to 44 ppm Au. The initial land-based analyses (INAA) reveal a maximum gold value of 45 ppm Au and an average gold concentration of 18 ppm Au

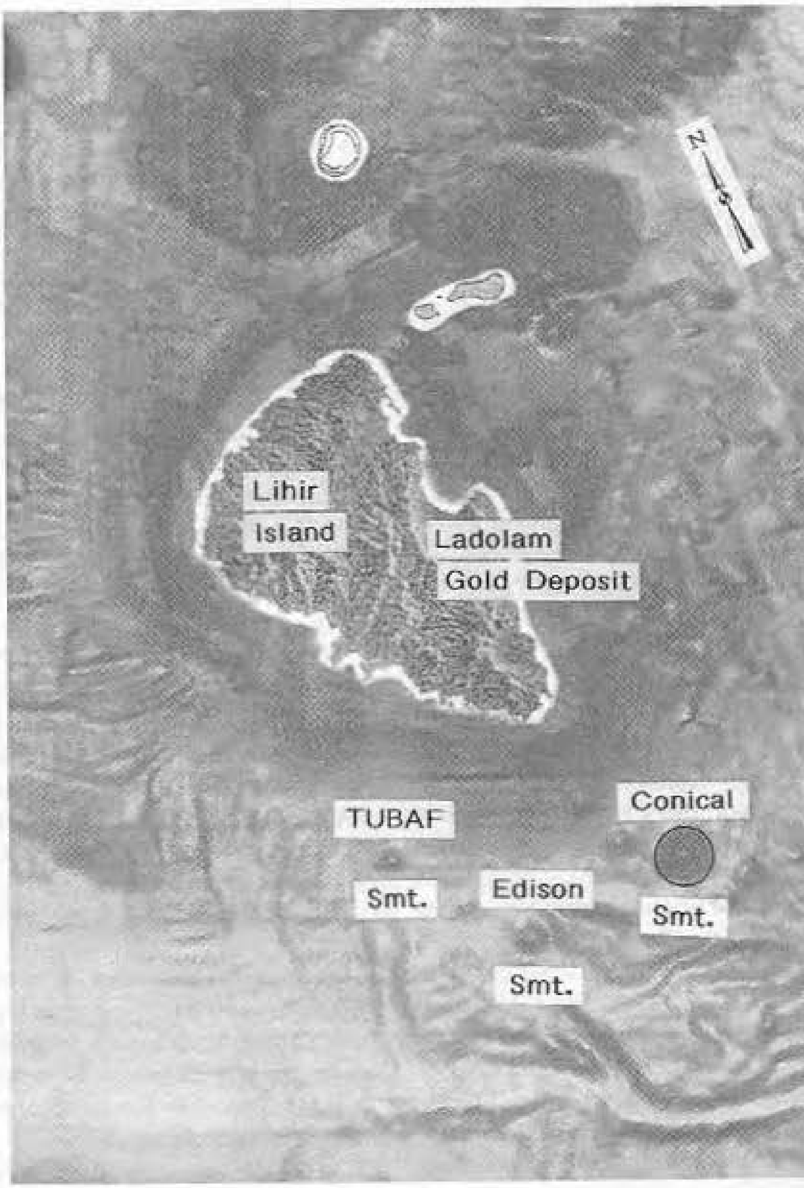

Figure 2. Perspective view of Lihir Island hosting the Ladolam epithermal gold deposit and the location of Conical, Edison, and TUBAF seamounts.

for mineralized samples (n=26). Gold-rich sulfides also contain between 420-1020 ppm Ag.

The present mapping and sampling suggests that the entire upper part of the volcano may be mineralized at depth, however, the difficulty of sampling the broken flows prevents a proper assessment of the 3rd dimension. Drilling of the summit area is required to determine the extent and character of mineralization at depth. The base metal-rich sulfide assemblage and the style of alteration most closely resembles that of low-sulfidation epithermal vein systems on land and have many similarities with the giant 40 million ounces epithermal Ladolam gold deposit on the island of Lihir.

The discovery of epithermal style gold mineralization at Conical Seamount represents a new type of seafloor mineralization. Massive sulfides were not observed, suggesting that relatively little of the hot spring fluid vented onto the seafloor. The proximity of the Conical Seamount deposit to the presently active hot spring environment of the Ladolam deposit suggests that both submarine and subaerial epithermal mineralization may be linked to the same district-scale magmatic events.

Hydrothermal Activity & Cold Seeps

In 1994 evidence for active hydrothermal venting was found at Edison Seamount, where two extensive clam beds associated with diffuse fluid flow were discovered near the crest of the pyroclastic cone (Herzig et al., 1994). The clam beds occur on heavily sedimented surfaces at the crater rim and are surrounded by darkened muds that are stained by sulfide. Samples of the sediment collected in the TV-grab consist of pale green, foraminiferal carbonate ooze with minor smectite, amorphous Fe-sulfides and trace pyrite. Large slabs of indurated sediments and semi-lithified, volcaniclastic breccias in a matrix of foraminferal ooze were also recovered from the clam fields and form a hardened layer up to 10 cm thick, immediately surrounding the vent fields. 4.5 kHz bottom-profiling suggests that layers of indurated sediments may form an extensive carapace over the top of the cone and this may be important for concentrating fluid flow at the crater rim.

The presence of a mussel type, known elsewhere to have methanotrophic symbionts normally associated with cold seeps, and the abundance of carbonate-cemented crusts at Edison Seamount suggests that some of the present diffuse venting may be of cold seep origin rather than hydrothermal. The age of the cone and its location at the intersection of several major fault structures that are leaking CH_4 support this idea. However, the high density and enormous biomass of the clam fields far exceeds that found at cold seeps, and more closely resembles that of H_2S-rich vents associated with higher-temperature hydrothermal activity.

During investigations of a large, near-bottom methane anomaly initially observed in 1994, a major source of methane was located along an uplifted sediment block (horst structure) southeast of Edison Seamount. A maximum concentration of 9000 nl/l CH_4 was measured along the east-facing slope of the horst, opposite Edison Seamount, and this source likely accounts for a widespread mid-depth methane anomaly in the area. No temperature anomaly was observed. Several camera tows and TV-grabs in the area revealed discontinuous cold seep biota over a strike length of at least 2 km, centered on the highest methane anomaly. Large blocks and slabs of carbonate crusts and carbonate-cemented muds recovered from the slopes contain abundant flow channels stained by sulfide. Similar cold seeps were also observed on the southeast flank of a small volcanic cone north of Edison Seamount. This cone may be partly dissected by the fault which is presently leaking methane further to the south. The extensive carbonate cementation is thought to be related to the oxidation of methane within the upper part of the sediment profile. Gas charged (H_2S- and CH_4-rich) sediments were recovered in a core from this area, and obvious gas cavities were found in the sediment cores. White patches were also observed at the locations of the seeps, and these may be an indication of bacterial mats or solid gas hydrates. However, no samples of this material could be recovered. The liberation of methane from gas hydrates in the sediments may be related to the high heat flow in the area or local uplift associated with the rising basement high of the Lihir island group.

The discovery of methane degassing along major structural elements in an active tectonic zone of the New Ireland Basin and widespread faunal communities along the faults may be an indication of the presence of cold seeps similar to those found at accretionary margins (e.g., Cascadia Margin). If the presence of solid methane hydrates is confirmed, this site may be the first documented example of gas hydrates in an intra-arc setting.

Biological Communities

Mapping and sampling of Edison Seamount has established an important time series on the development of mature chemosynthetic biological communities in the region. Large beds of giant clams discovered in 1994 were resampled along with other fauna typically associated with sulfide-rich hydrothermal vents. Additionally a number of new fauna were discovered at this site. Camera surveys during SO-133 suggest that these clam beds may have expanded compared to 1994 and an increase in the population density is apperent.

Sulfide-specific fauna are absent at the edge of the clam beds, but a mussel type normally associated with cold seeps was observed. This type of mussel can have either H_2S- or CH_4-oxidizing symbionts, and further work on the samples is required to identify the bacteria present. Evidence for both H_2S and CH_4 in the fluids would support the idea that a portion of the nutrient flux at Edison may be related to nearby leaky fault structures that

International Ridge-Crest Research: **Back Arc Basins:** Herzig et al. continued...

are degassing CH_4. However, the biomass associated with Edison Seamount is much greater than that observed at the cold seeps, suggesting that a thermal flux associated with the volcano may be enhancing the availability of reduced gases.

On the nearby fault structure, southeast of Edison Seamount, another assemblage of animals was recovered with a quite different character. Mussels and polycheates at this site have colonized areas of carbonate concretions, and both vesitmentiferans and polycheates were collected from the sediments. However, the biomass encountered was considerably lower than in the clam beds at Edison Seamount. High concentrations of methane in the escaping fluids likely contribute the largest part of the nutrient base for the observed biological community.

The presence of diverse biological communities in the vicinity of Edison Seamount suggests two different but closely juxtaposed styles of venting (warm springs and cold seeps). The warm fluids are likely influenced by volcanic processes causing enrichment in reduced sulfur, whereas cold fluids channeled through tectonic features may be remobilizing buried carbon and emerging as fluids enriched in both methane and sulfur. Clams, mussels, and vestimentiferans are known at both warm vents and cold seeps, but many of the animals found at Edison (crabs, shrimps, barnacles, limpets) have their closest relatives at mid-ocean ridges and back-arc hydrothermal sites. Many of the animals at Edison and at the nearby cold seeps are likely to be new species and thus represent a fauna specific to this region. The animals are different from the vent fauna in the nearby Manus Basin and may indicate the presence of a large endemic population elsewhere in the New Ireland Basin.

Acknowledgements

Principal funding of this research was provided by the German Federal Ministry for Education, Science, Research and Technology (BMBF Grant No.03G0133A to PMH). Additional support was provided by Natural Resources Canada (Geological Survey of Canada). We thank Master H. Andresen and the officers and crew of *RV Sonne* for their expert technical assistence during this cruise.

References

Exon, N.F., W.D. Stewart, M.J. Sandy and D.L. Tiffin, Geology and offshore petroleum prospects of the eastern New Ireland Basin, northeastern Papua New Giunea. BMR *J. Aust. Geol. Geophys.* 10: 39-51, 1996.

Gulf Research and Development. *Regional marine geophysical reconnaissance of Papua New Guinea.* Gulf Research and Development Company and Australian Gulf Oil Company, Sydney, 1973.

Hedenquist, J.W. and J.B. Lowenstern, The role of magmas in the formation of hydrothermal ore deposits. *Nature*, 370: 519-527, 1994.

Herzig, P.M. and M.D. Hannington, Hydrothermal activity, vent fauna, and submarine gold mineralization at alkaline fore-arc seamounts near Lihir Island, Papua New Guinea. Proceedings Pacific Rim Congress 1995 *Australasian Institute of Mining and Metallurgy*: 279-284, 1995.

Herzig, P.M., M.D. Hannington, B. McInnes, P. Stoffers, H. Villinger, R. Seifert, R. Binns, T. Liebe, and Scientific Party *RV Sonne* Cruise SO-94 Submarine volcanism and hydrothermal venting studied in Papua New Guinea. *EOS, Transactions American Geophysical Union*, 75: 513-516, 1994.

Herzig, P.M. and K.-P. Becker (eds), Tectonics, Petrology and Hydrothermal Processes in Areas of Alkaline Island-Arc Volcanoes in the Southwest Pacific: The Tabar-Lihir-Tanga-Feni Island Chain, Papua New Guinea. Final Report SO-94. 289 pp., 1996.

Johnson, R.W., D.A. Wallace and D.J. Ellis, Feldspathoid-bearing potassic rocks and associated types from volcanic islands off the coast of New Ireland, Papua New Guinea: a preliminary account of geology and petrology. In: *Volcanism in Australasia*, Johnson, R.W. (ed), Elsevier, Amsterdam: pp. 297-316., 1976

Licence, P.S., J.E. Terril and L.J. Fergusson, Epithermal gold mineralization, Ambittle Island, Papua New Guinea: In: *Proceedings Pacific Rim Conference '87*: Australian Institute of Mining and Metallurgy, Melbourne: pp. 273-278., 1987.

McInnes, B.I.A. A glimpse of ephemeral subduction zone processes from Simberi Island, Papua New Guinea. Ph.D. thesis, University of Ottawa, Canada: 235 pp., 1992

McInnes, B.I.A., and E.M. Cameron, Carbonated, alkaline metasomatic melts from a sub-arc environment: Mantle wedge samples from the Tabar-Lihir-Tanga-Feni arc, Papua New Guinea, *Earth Planet. Sci. Lett.*, 122: 125-141., 1994.

Moyle, A.J., B.J. Doyle, H. Hoogvliet and A.R. Ware, Ladolam gold deposit, Lihir Island. In: *Geology of the Mineral Deposits of Australia and Papua New Guinea*, F.E. Hughes (ed), Vol. 2: 1793-1805, 1990.

Port Moresby Geophysical Observatory. *Earthquake map of the PNG region 1964-1994*, 1994.

Stewart, W.D. and M.J. Sandy, Geology of New Ireland and Djaul Islands, Northeastern Papua New Guinea. In: *Geology and Offshore Resources of Pacific Island Arcs - New Ireland and Manus region, Papua New Guinea,* M.S. Marlow, S.V. Dadisman and N.F. Exon (eds) Circum-Pacific Council for Energy and Mineral Resources, Earth Science Series 9: 13-30, 1988.