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

Longitudinal Transect of the Kermadec – Havre Arc – Back-Arc System: Initial Results of *R/V Sonne* Cruise SO-135

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Introduction

Cruise SO-135 of *RV Sonne* completed an extensive mapping and sampling program at selected sites along a longitudinal transect of the active Kermadec arc – Havre back-arc system (SW Pacific), and its southern extension into the offshore Taupo Volcanic Zone (TVZ) of central North Island, New Zealand (Fig. 1). To the north the Lau Basin back-arc, and volcanism of the Tofua arc, are associated with subduction at the Tonga Trench. The *RV Sonne* cruise was a collaborative German – New Zealand project involving a consortium of five German universities, three New Zealand research groups, and other invited researchers. SO-135 was the second of a series of recently completed and/or planned cruises, to this arc – back-arc system. The underlying theme of these cruises is to characterise longitudinal variations of tectonic and magmatic processes along the arc – back-arc system at different crustal settings, and to identify sites of associated hydrothermalism. The cruise (Sept.-Oct. 1998) comprised two legs from Suva-Auckland-Wellington, with the first completing a series of detailed mapping and sampling studies along the Kermadec arc, and central Havre Trough, while the second leg consisted of sampling, including manned JAGO submersible dives at shallow hydrothermal vents of the offshore TVZ.

Geological Setting

The Tonga-Kermadec-Taupo (TKT) arcs, and the ssociated Lau-Havre-Taupo (LHT) back-arc system, form an active, contiguous arc–back-arc system extending over 2000 km between Tonga and New Zealand along the Pacific–Australian convergent margin. The general structure comprises the LHT back-arc, and to a lesser degree the TKT arc, progressing southward through different crustal settings (Parson and Wright, 1996), although collision of seamount chains, and possibly submarine plateaus, into the subduction margin overprint the system along its length. The LHT propagates southwards with spreading oceanic propagation into oceanic crust (central Lau Basin), oceanic propagation into arc crust (southern Lau Basin), rifting within arc crust (Havre Trough), and rifting within continental crust (central North Island, New Zealand).

The continuum of an arc–back-arc system through full oceanic spreading to continental crustal rifting raises a number of fundamental issues including:

(1) What tectonic and magmatic processes are involved in the development of a mature arc spreading back-arc from an immature arc rifting back-arc system?

(2) Do these processes vary spatially and temporally (including longitudinally and across the arc)?

(3) Does proximity to a subduction zone modify the underlying tectonic and magmatic processes?

(4) Does rift and arc magmatism (in-

cluding associated hydrothermalism) vary between continental, arc, and oceanic crustal settings?

Specific sectors of the LHT system are becoming comparatively well-studied. Considerable data exists for the (1) central and southern Lau oceanic spreading ridge propagation (Parson et al., 1990; Wiedicke and Collier, 1993; Parson and Hawkins, 1994) and southern Lau rift (Matsumoto et al., 1997), (2) the northernmost Havre Trough (Matsumoto et al., 1997), and (3) the southernmost Havre Trough (Wright et al., 1996) and onshore Taupo continental rifting segment (Wilson et al., 1995). However, critical gaps along the system are the central Havre Trough – Kermadec Ridge sector (between 28-32°S); and the offshore TVZ. Additionally, the character and distribution of hydrothermalism is poorly established along the Kermadec – Havre sector, although active hydrothermal systems are known at both the northern and southern extensions from the Lau Basin (Fouquet et al., 1991) and TVZ (Hedinquist, 1986). Hydrothermal sites within the Kermadec–Havre sector have been recently discovered at Brothers and Rumble II West arc calderas (Wright et al., 1998), however, it is uncertain whether they are presently active.

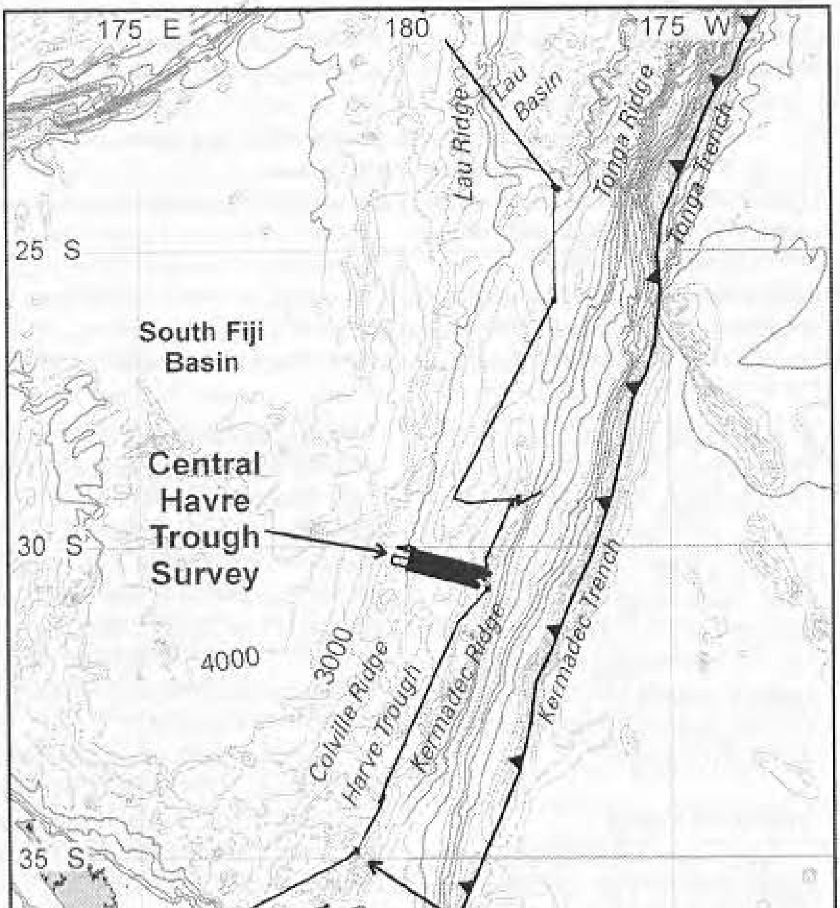

Figure 1. Regional structure (SW Pacific) and the ship track of *RV Sonne* cruise SO-135.

Cruise Objectives

The underlying scientific objectives of SO 135 were to:

(1) Determine the characteristic morphology and volcano-tectonic fabric of back-arc rifting and associated volcanism within the central Havre Trough, including spatial and temporal variations,

(2) Establish the petrogenetic characteristics and relationships of rifting magmatism and arc volcanism, and possible longitudinal variations in magmatism along the modern Kermadec arc front between arc and continental crust,

(3) Locate, quantify, and determine the setting of possible hydrothermalism and active venting along targeted sectors of the Kermadec – Havre arc–back-arc system, and

(4) Further characterize and sample submarine hydrothermal vents within the continental offshore TVZ, near the active White Island arc volcano.

Central Havre Trough Rifting

The central Havre Trough forms an archetypal segment of an arc–back-arc system (Karig, 1970, Taylor and Karner, 1983) comprising the remnant Colville arc, Havre Trough back-arc complex, and the active Kermadec arc and frontal ridge. The latter including the partially emergent island volcanoes of Macauley, Curtis Islands, and Raoul Islands. The back-arc complex consists of a central volcanic basement high, flanked by western and eastern sedimentary sub-basins. Hydrosweep multibeam and magnetic anomaly data, and multichannel seismic (MCS) profiles (145-165 km in length) reveal the back-arc rifting fabric between 30-30°40'S (Fig. 2).

The remnant Colville arc comprises volcanic basement with overlying sequences of volcaniclastic sediments that are down-thrown by a series of listric normal faults to the east. The basal sequences are extensively faulted at depth, and record both the early phases of arc volcanism, and the earliest phases of arc rifting. The border fault zone, between the remnant arc and western sub-basin, has an apparent *en echelon* configuration, generally striking between 019 and 038. Syntectonic volcanism is evinced by volcanic edifices along the fault zone.

The western sedimentary sub-basin consists of a sedimentary sequence (with thickness of 0.4 - 0.8 sec TWT) partially mantling volcanic basement. Out-of-plane seismic reflections and isolated knolls observed within the multi-beam data indicate that the underlying basement has a variable morphology. The basement fabric, where observed, is orientated 041-043. The overlying sedimentary sequence shows basin infilling was dominantly from the west, with little evidence of subsequent extensional faulting.

The central volcanic high has a 12-35 km wide basement block, with minor or no sediment cover, which rises ~200-800 m above the flanking sediment basins. It has a strong linear fabric with bimodal structural trends of 021-031 and 063. Such trends are consistent with other oblique Havre Trough rifting basement fabrics (Caress, 1991; Wright, et al., 1996). The more oblique orientations appear to occur along the eastern margin of the central volcanic block. The eastern sedimentary sub-basin is the main site of present-day extensional faulting, with a pervasively faulted sedimentary sequence of variable thickness of up to at least 1 sec TWT. Faults predominantly dip west, with the larger having seafloor relief and late Quaternary syntectonic deposition on the hanging-wall. In the south, where the basin narrows to a 10 km wide rift, flanking basement horsts have strike orientations of 043-055.

The Kermadec Ridge is interpreted to comprise a basement core of the older proto-Colville-Kermadec arc and associated volcaniclastic sequences possibly 10-5 Ma in age, capped with arc volcanoes of the present-day arc front. The entire volcaniclastic sequence consists of an upper sedimentary section overlying a chaotic sequence of discontinuous reflectors that in part may represent intercalated sequences of old volcaniclastic sediments and true acoustic basement. The lower section may be better imaged following processing of the MCS data. Border faults along the lower western flank, generally orientated 025, are interpreted as a series of low-angle normal faults with seafloor relief of 100-300 m. These faults dip west and show evidence of back-tilting and syntectonic deposition.

Rock samples dredged from across the entire arc–back-arc system comprise mostly highly vesicular, aphyric

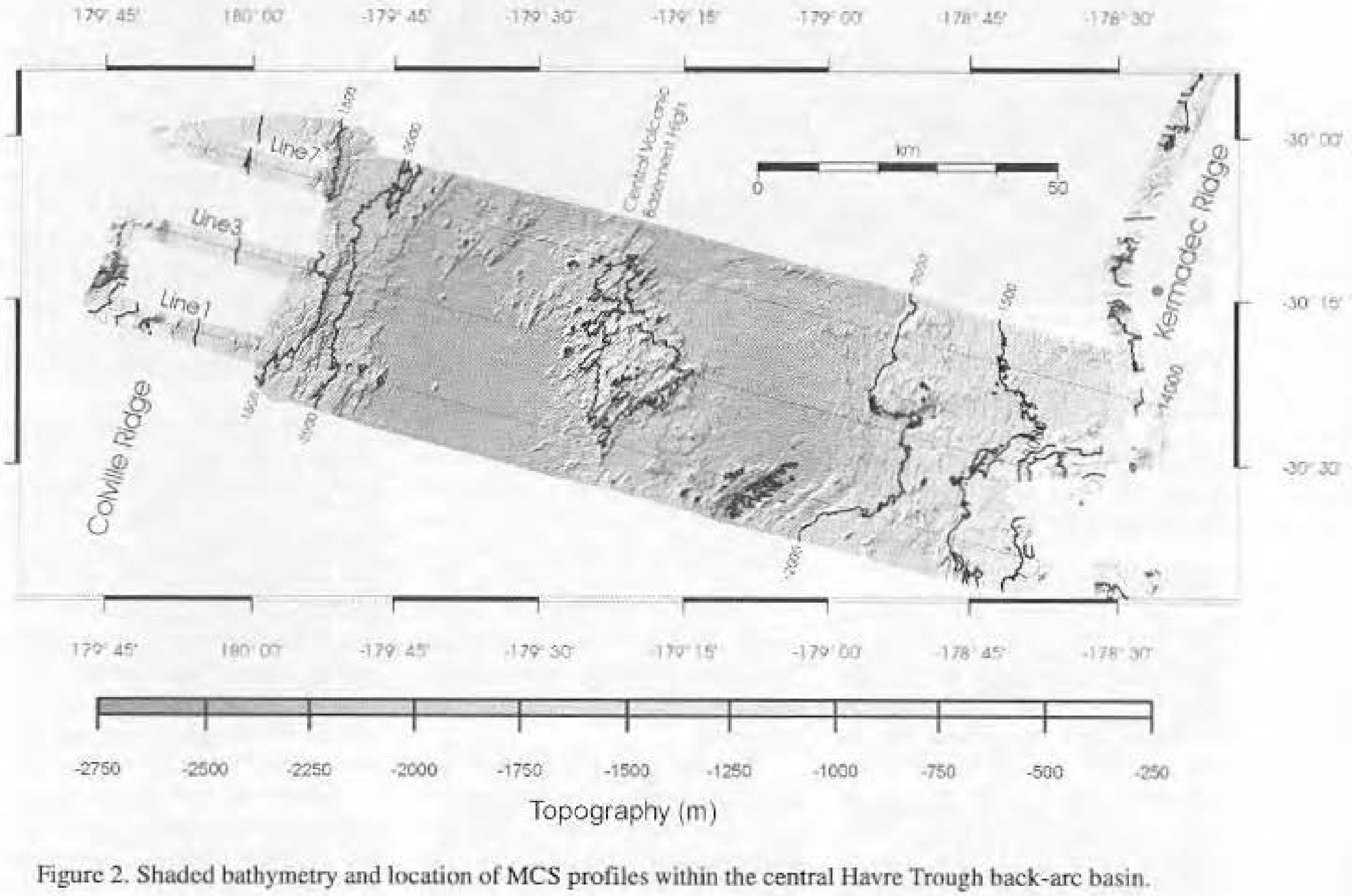

Figure 2. Shaded bathymetry and location of MCS profiles within the central Havre Trough back-arc basin.

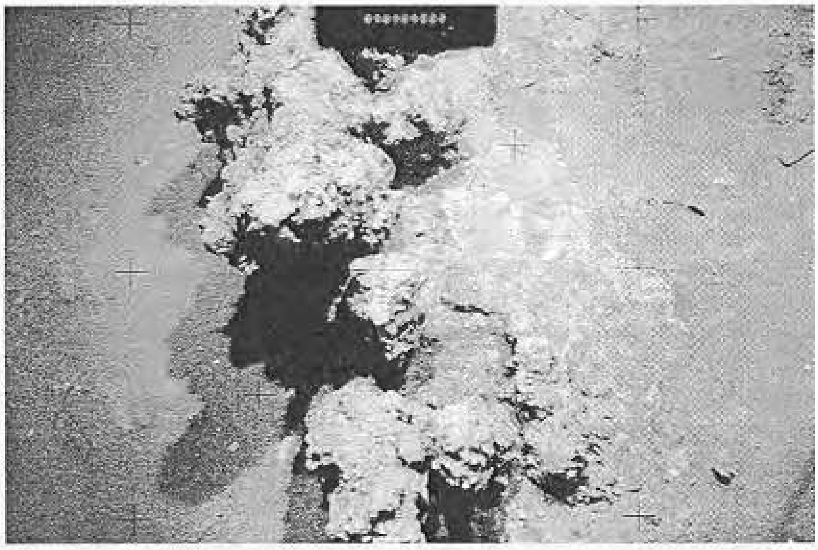

Figure 3a. Chimney and associated massive sulfides and talus from the inner north wall of Brothers caldera.

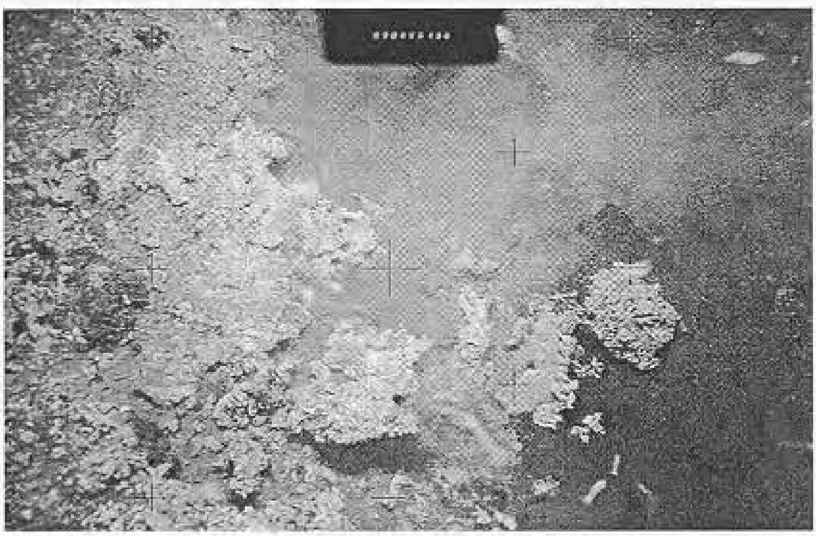

Figure 3b. Shrimps near the vicinity of black smoker vents on the lower north wall of Brothers caldera.

lavas, with 2 cm Mn encrusting, palagonite, and rock "weathering" increasing to the west.

Brothers Arc Caldera

The Brothers arc caldera (34°52'S, 179°04'E), a volcano of the southern Kermadec arc initially discovered with MR1 swath mapping, is one of only two known sites of deep-water, high-temperature hydrothermalism in the Kermadec-Havre system (Wright et al., 1998). Prior to cruise SO-135 two sites of sulfide mineralisaton associated with hydrothermal venting on the caldera wall, and the recovery of two partial specimens of the caridean vent shrimp suggested that Brothers caldera was an active hydrothermal system. SO-135 studies at the Brothers caldera entailed multibeam mapping, seafloor video/camera surveys, rock sampling, and reconnaissance water-column sampling.

The volcano is part of larger volcanic arc complex comprising elongate ridges/extensional fractures and depressions orientated 050-060. The edifice proper rises to a general caldera rim water-depth of 1560 m, although locally the northwest caldera rim shoals to 1320 m. The elongate-cresentic caldera partially encircles an elongate 1.5-2 km wide, and 350 m high, resurgent dome cone that, in part coalesces with the inner, southern caldera wall. The caldera varies between 3-3.5 km in diameter, with the caldera wall rising some 350-450 m above the caldera floor. Evidence of faulting and mass-wasting of the caldera wall are common.

The seafloor imaging and sampling revealed the presence of extensive hydrothermal mineralization, active high-temperature "black smoker" venting, and localized vent fauna on the north and southern caldera walls, and on the resurgent dome.

North Wall

Coincident with the original massive sulfide discovery a significant site of sulfide mineralisation and active hydrothermal venting occurs on the northern caldera wall along escarpments in water-depths of 1550-1650 m. Four active black smoker vents (with 1-2 m high chimneys) were observed. The largest contiguous zone of sulfide mineralization, 50 m in width and nearly 500 m in strike length, occurs along a narrow escarpment at about 1650 m water depth. Numerous, free-standing chimneys, measuring 1-5 m in height and having abundant sulfide talus and massive sulfides, were observed (Fig. 3a).

Black smoker vents and inactive chimneys also occur higher up on the northern caldera wall (small fields up to 25 m across), while a partially buried relict vent field occurs on a low escarpment near the sediment-covered caldera rim. The latter consists of discontinuous zones of eroded sulfide material and standing chimneys with a total strike length of about 400 m. Shimmering water was observed locally near the caldera rim.

Recovered hydrothermal rocks include 6 main sample types: (1) pyrite-anhydrite breccias; (2) a massive sphalerite chimney, (3) massive pyrite crusts, (4) massive pyrite breccias, (5) pyritic stockwork material, and (6) Fe-oxide-silica crusts.

The massive anhydrite breccias consist of crystalline anhydrite and minor disseminated pyrite. Complex breccias containing large clasts of pyrite and anhydrite in a matrix of coarser-grained anhydrite are interpreted to be the erosional remnants of anhydrite mounds and/or chimneys.

A single, intact sphalerite chimney was recovered by dredging of the lower caldera wall. The interior of the chimney is distinctly zoned, with an inner core of porous sphalerite and pyrite and an outer zone of amorphous silica, pyrite and marcasite. Minor chalcopyrite lines an internal conduit, with macroscopic galena intergrown with the sphalerite.

Pyritic stockwork-like consists of massive pyrite-cemented breccias, containing pyrite and clasts of intensely altered dacite, and pyrite-silica breccias comprising large clasts of silicified dacite with abundant disseminated pyrite in the matrix. The former contain traces of sphalerite and chalcopyrite, and euhedral anhydrite.

Large areas of the upper caldera wall and rim are covered by delicate Fe-silica crusts which appear to have formed at low-temperature vents and along fractures in the more massive dacite flows. Most of the crusts consist of brecciated fragments, probably formed by the repeated growth and collapse of small Fe-silica chimneys at the deposit margins.

Although vigorous venting of black smoke was observed, obvious vent-specific macro-fauna were not abundant. The presence of clam shells, bacterial floc, and stalked barnacles suggests that a vent fauna assemblage was once present, but is now sparse. A few barnacles, galatheid crabs, minor filamentous bacteria, and shrimps (Fig. 3b) were the only living fauna associated with the current hydrothermal activity.

South Wall

Grey altered talus occurs at the base of the south wall, suggesting that much of this portion of the caldera may have been exposed to hydrothermal fluid. No obvious sulfide mineralization was observed and no samples were recovered from this location.

Resurgent Dome

The resurgent dome comprises extensive glassy dacite talus and a large 300 m zone of Fe-oxide staining and alteration at the crest. A large near-bottom plume was observed near the dome crest, but an obvious vent source could not be located. Fresh, glassy, vesicular dacite dredged from the northern flank of the dome was locally encrusted with native sulfur and Fe-oxides. Vent-related fauna include sulfide worms, limpets, white filamentous bacteria, shrimp, and several large fields of stalked barnacles.

Offshore TVZ (SW White Island)

The offshore TVZ, southwest of the active White Island volcano, forms a region of known submarine hydrothermal venting with observations of gas bubbling, metalliferous sediments, and anhydrite mounds (Duncan and Pantin, 1969; Glasby 1975; Sarano et al., 1989). Known sites of hydrothermal venting (including the Calypso vents) occur within a zone of late Quaternary extensional faulting (the offshore segment of the Whakatane Graben), and appear to be associated with active normal faults (Pantin and Wright, 1994). SO-135 studies at these sites entailed multibeam mapping, seafloor video /camera surveys, rock sampling, and JAGO submersible sampling and observations.

Multibeam mapping reveal that the outer continental shelf is disrupted by a series of TVZ faults (including the White Island fault zone) striking 044°-053. Typically the faults have seafloor expression comprising elongate depressions, tilted blocks, and raised ridges, all of which have vertical relief of 5-20 m. The faults appear to be segmented over strike lengths of 5-7 km. Three major hydrothermal vent site areas, initially identified by acoustic back-scattering from columnar bubble zones streaming to the sea-surface were identified at 37°41.7'S, 177°06'E; 37°41.3'S, 177°07.4'E; 37°35.8'S, 177°06.2'E (the Calypso vents).

Northern Vent Area (Calypso Vents)

The northern vent area comprises a number of vent sites within a 1.5 km^2 area. Most recovered samples comprise altered pumiceous ash and sulfur-cemented breccias, and localised anhydrite. Disseminated pyrite (as < 1 mm grains) is abundant in the clay-altered pumiceous ash. The massive anhydrite shows evidence of corrosion, dissolution, and extensive reworking, and is interpreted to be the eroded remnants of an anhydrite mound or chimney, possibly that described by Sarano et al. (1989).

Southern Vent Area

Vents in the southeast and southwest areas generally occur as individual vent outlets occupying small depressions (1-5 m in diameter) adjacent to the faults, and clustered within ~500 m^2 areas. Specific vent sites appear to be localized by collapse features along fault scarps, and zones of intense silification which focus fluid flow. Venting fluid temperatures are 180-201°C. The silicified sediments occur as large, flat-lying and sometimes tilted slabs that are exposed along the fault scarps, and mantled with bacterial filaments, sponges and anemones.

Within the vent areas most recovered samples contain abundant native sulfur, and locally pyrite. In more silicified rocks, veins of pyrite up to 1 cm wide are observed and cut silicified ash beds. Black, sulfide-stained blocks of pumiceous ash and volcanic breccia were also recovered, many of which were impregnated with light hydrocarbons in fractures and pore spaces. Some 30-40% of samples are intensely mineralized containing abundant pyrite, orpiment, realgar, mercury (cinnabarnative mercury), and native sulfur.

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References

Caress, D.W., Structural trends and back-arc extension in the Havre Trough. *Geophys. Res. Lett.*, 18: 17-19, 1991.

Duncan, A.R. and H.M. Pantin, Evidence for submarine geothermal activity in the Bay of Plenty. *N.Z. J. Mar. Freshwater Res.*, 3: 602-606, 1969.

Fouquet, Y., U. von Stackelberg, J.L. Charlou, J.P. Donval, J.P. Foucher, J. Erzinger, P. Herzig, R. Muhe, M. Wiedicke, S. Soakai, and H. Whitechurch, Hydrothermal activity in the Lau back-arc basin: Sulfides and water chemistry, *Geol.*, 19: 303-306, 1991.

Glasby, G.P., Geochemical dispersion patterns associated with submarine geothermal activity in the Bay of Plenty, New Zealand. *Geochem. Jour.*, 9: 125-138, 1975.

Hedenquist, J.W., Geothermal systems in the Taupo Volcanic Zone: their characteristics and relation to volcanism and mineralisation, in: Late Cenozoic Volcanism in New Zealand, I.E.M. Smith, ed., pp. 7-20, *Roy. Soc. N.Z. Bull. 23*, 1986.

Karig, D.E., Ridges and basins of the Tonga-Kermadec Island arc system. *J. Geophys. Res.* 75: 239-254, 1970.

Matusmoto, T.; K. Kobayashi, T. Yamazaki, J. Deltiel, E. Ruellan, S. Abe, M. Aoki, G. Buffet, C.J.E de Ronde, J. Etoubleau, T. Fujiwara, P.A. Jarvis, M. Joshima, T. Kula, H. Kumagai, F. Murakami, A. Nishizawa, A. Pelletier, N. Takahaski, and I.C. Wright, Boundary between active and extinct zones in the Lau Basin-Havre Trough, Southwest Pacific: Results of the LAUHAVRE cruise of *R/V Yokosuka*. *InterRidge News* 6(2): 19-24, 1997.

Pantin, H.M. and I.C. Wright, Submarine hydrothermal activity in the offshore Taupo Volcanic Zone, Bay of Plenty continental shelf, New Zealand. *Continent. Shelf Res.*, 14: 1411-1438, 1994.

Parson, L.M. and J.W. Hawkins, Two-stage ridge propagation and the geological history of the Lau back-arc basin. *Proc. ODP, Sci. Res.*, 135: Ocean Drilling Program, College Station, TX, 819-828, 1994.

Parson, L.M. and I.C. Wright, The Lau-Havre-Taupo back-arc basin: A southward-propagating, multi-stage evolution from rifting to spreading. *Tectonophys.*, 263: 1-22, 1996.

Parson, L.M., J.A. Pearce, B.J. Murton, R.A. Hodkinson, S. Bloomer, M. Ernewein, Q.J. Hugget, S. Miller, L. Johnson, and P. Rodda, Role of ridge jumps and ridge propagation in the tectonic evolution of the Lau back-arc basin, southwest pacific. *Geol.*, 18: 470-473, 1990.

Sarano, F., R.C. Murphy, B.F. Houghton, and J.W. Hedenquist, Preliminary observations of submarine geothermal activity in the vicinity of White Island volcano, Taupo Volcanic Zone, New Zealand. *J. Roy. Soc. N.Z.* 19: 449-459, 1989.

Taylor, B. and G.D. Karner, On the evolution of marginal basins, *Rev. Geophys. Space Phys*, 21: 1727-1741, 1983.

Wiedicke, M. and J. Collier, Morphology of the Valu Fa Spreading ridge in the southern Lau Basin. *J. Geophys. Res.*, 98: 11,769-11,782, 1993.

Wilson, C.J.N., B.F. Houghton, M.O. McWillimas, M.A. Lanphere, S.D. Weaver, and R.M. Briggs, Volcanic and structural evolution of Taupo Volcanic Zone, New Zealand: A review. *J. Volc. Geotherm. Res.*, 68: 1-28, 1995.

Wright, I.C., L.M. Parson, and J.A. Gamble, Evolution and interaction of migrating cross-arc volcanism and backarc rifting: An example from the southern Havre Trough (35°20'-37°S). *J. Geophys. Res.*, 101: 22071-22086, 1996.

Wright, I.C., C.E.J. de Ronde, K. Faure, and J.A. Gamble, Discovery of hydrothermal sulfide mineralisation from southern Kermadec arc volcanoes (SW Pacific). *Earth Planet. Sci. Lett.*, 164: 335-343, 1998.

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