# VOYAGE SUMMARY SS02/2003

**Title**
Submarine hydrothermal plume activity and petrology of the Eastern Lau Spreading Centre and neighbouring Tofua Arc, Tonga

**Itinerary**
Departed Auckland (NZ) 1800 hrs, Friday 14 March, 2003
Arrived Nuku'alofa (Tonga) 1000 hrs, Thursday 3 April, 2003

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**Scientific Objectives**
At the southern end of the Lau backarc basin, the Valu Fa Ridge of the Eastern Lau Spreading Centre (ELSC) hosts one of the most active hydrothermal systems on the planet. The ELSC is propogating southwards into pre-existing Lau backarc Basin crust, and the spreading axis gradually approaches (to about 40 km) the axis of the Tofua arc. The Tofua arc itself is highly active with numerous submarine eruptions reported in the last 50 years. Thus within a relatively confined region geographically, highly active, submarine arc and backarc systems are in close proximity. Systematic petrologic and geochemical linkages between arc and backarc axes provides a superb opportunity to understand the fundamental underlying processes of melt transfer from mantle to crust with accompanying volatiles in a suprasubduction zone setting.

The major scientific objectives are a study of the hydrothermal plume activity with systematic vertical hydrocasts (including CTD-optical profiling) and "tow-yos" to map plume sizes, their distributions, and to characterize their chemical signatures. We will couple this effort with sample grabs and dredges. In addition, we will build upon established success with hydrocasts and tow-yo's in the southern Kermadec arc (NZAPLUME voyage) in pursuit, detection and sampling of hydrothermal (and $^{3}He$) plumes from intra-and cross-arc edifices.

Specific objectives are:
1. To perform the first systematic survey of hydrothermal activity along an incipient back arc spreading ridge (3 segments of Valu Fa Ridge extending 150 km) and compare the intensity and chemistry of that activity to magmatic-hydrothermal emissions along an adjacent volcanic arc section (southern Tonga arc).

2. We will extend the same plume-location/charaterization approach to the adjacent active Tofua arc where one active subaerial volcano (Ata) is known but a number of active submarine centres have been inferred. Of particular interest is the possibility of submerged rhyolitic calderas which are now known to alternate with subaerial (mafic-dominated) centres in the Izu-Bonin arc, and to be highly mineralised. Similarly, the major objective in the arc domain is to characterise chemical compositions and fluxes of the plumes for eventual quantitative calculations of mass (volatiles and metals) fluxes.
3. In both backarc and arc environments, we will execute video camera tows to image hydrothermal activity, and recover fresh glassy rock samples for detailed chemical analysis, particularly of volatile elements and compounds, and stable isotopic characteristics.

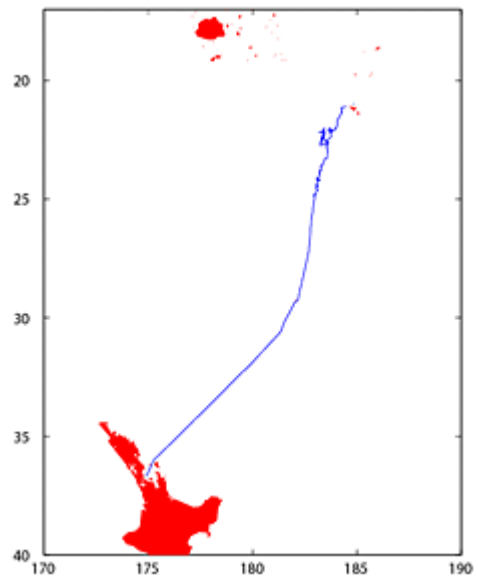
**Voyage Objectives**

We will sample along the axis of the Valu Fa Ridge, the Tofua Arc between about 21°30' and 24°10'S, and one transverse hydrothermal cast from the backarc to arc region at ~ 22°30'S. More specifically, objectives of the voyage are:

1. Perform a continuous along-axis survey for hydrothermal activity along the three segments of the Valu Fa back arc spreading ridge. At sites of intense plume activity, provide cross-axis surveys in order to provide a three-dimensional image of plume distribution and for thermal and chemical inventory purposes. Conduct vertical CTD-sampling profiles along the survey section (on return transit).
2. To the extent possible, conduct a systematic survey for hydrothermal activity along the S. Tonga arc adjacent to the Valu Fa ridge. Perform vertical casts over all identified arc volconoes within a continuous survey section and cross-volcano tow-yos at selected sites. Define the adjacent ocean water with respect to survey parameters in order to construct arc section distributions of hydrothermal properties.
3. Compare (for the first time) the incidence and chemistry of hydrothermal emissions along the adjacent back arc ridge and volcanic arc sections.
4. Coordinate results of back arc ridge survey with RIDGE 2000.

**Voyage Track**

Figure 1. Overall voyage track of from Auckland to Tonga via the Tofua Arc and Valu Fa Ridge



**Results**

The major scientific objectives of the voyage were a study of the hydrothermal plume activity of the Tofua Arc and adjacent Valu Fa back arc Ridge coupled with sampling of the sea floor with grabs and dredges. Quoting the Voyage Plan, " we will sample along the axis of the Valu Fa Ridge, the Tofua Arc between about 21° 30" and 24° 10'S, and one transverse hydrothermal cast from the backarc to arc region at ~ 22° 30'S". More specifically, objectives of the voyage were:

1. perform a continuous along-axis survey for hydrothermal activity along the three segments of the Valu Fa back arc spreading ridge. At sites of intense plume activity, provide cross axis surveys in order to provide a three-dimensional image of plume distribution and for thermal and chemical inventory purposes. Conduct vertical CTD-sampling profiles along the survey section (on return transit).
2. To the extent possible, conduct a systematic survey for hydrothermal activity along the S. Tonga arc adjacent to the Valu Fa Ridge. Perform vertical casts over all identified arc volcanoes within a continuous survey section and cross-volcano tow-yos at selected sites. Define the adjacent ocean water with respect to survey parameters in order to construct arc cross section distributions of hydrothermal properties.
3. Compare (for the first time) the incidence and chemistry of hydrothermal emissions along the adjacent back arc ridge and volcanic arc sections.
4. Coordinate results of back arc ridge survey with RIDGE 2000 investigators slated to perform similar surveys further north on Lau back arc spreading ridges."

Voyage achieved these objectives. We were enormously assisted in meeting these objectives with efficient utilization of ship time through the generous provision by Dr's. P. Stoffers and T. Worthington of detailed swath maps of the Tofua Arc between 21° and 24° 50' S, and more detail than available previously of the southern Valu Fa Ridge. Without the availability of these types of map, a much larger proportion of the ship's time would have been used in single-trace echosounding to define the targets especially south of 22° S. Highlights of the objectives achieved by SS02/2003 are:

1. a systematic along axis survey completed for hydrothermal activity of the Valu Fa Ridge from the southern propogating tip at 22° 43' S northwards to 21° 58'S. There are several segments of the Ridge: southern, Hine Hina (or central), Vai Lili (or northern) and White Church (where the names refer to previously identified vent fields). We found very weak hydrothermal plumes are currently associated with the Hine Hina and Vai Lili fields. In contrast, we discovered new strong plumes (nephelometry, thermal, and Eh) centred about the northern end of the Hine Hina section at 22° 48' to 22° 45'S, northern end of the Vai Lili section at 22° 20' to 22° 17'S, and southern end of the White Church segment at about 22° 16'S. These plumes were initially identified in along axis tow-yos and mapped further with cross-axis tows and vertical hydrocasts. Two camera tows along the axis of the Ridge in the vicinity of the plume north of Vai Lili revealed a rugged and jagged topography dominated by remarkably highly sedimented, glassy dacite/andesite blocks, and a single small fluid vent.
2. A systematic survey for hydrothermal activity completed along the Tofua Arc between 24° 50'S (so-called Volcano 19 and (21° 9'S) at Volcano 1. This section includes a portion of the Tofua Arc south of the intersection with the Tonga Trench of the Louisville Ridge (intra-oceanic seamount chain) and no adjacent back arc, and the Tofua Arc adjacent to the spreading activity of the Valu Fa back arc Ridge. Of these volcanoes, 40% were found to be emitting hydrothermal plumes. The only structures not explored for hydrothermal activity were those identified by recent RV Sonne voyage (SO167) as apparently old, wave-base-planed edifices. This is the highest percentage of venting volcanoes for any arc that has yet been studied (Mid- and Southern Kermadecs, Marianas) using analogous systematic approaches. It is becoming clear that together with

hydrothermal plumes associated with mid-ocean and back arc ridges, the submerged portions of island arcs are significant contributors of chemical fluxes into the global oceans. We are now able to make an inventory of plume activity within arc and adjacent back arc environments for this portion of the Tofua arc.

3. We recovered a large number of rock and sediment samples through dredging of the Tofua Arc (, adjacent Valu Fa back arc Ridge, and a number of seamounts located between these two major magmatic loci . We achieved a high sample recovery success rate with use of the chain bag plus enclosed and open pipe dredge combination, and did not need to deploy the Smith-McIntyre grab. The excellent nature of the dredge recoveries and the pace with which these were returned to deck meant we did not use the "wax coring" technique that had been prepared for the ship's gravity corer. Along the Tofua Arc, we were guided by the experience of SO167 in recovering predominantly felsic pumices from several of the major, caldera-dominated edifices in seeking deeper, less prominent volcanic cones as targets. Many of these yielded mafic lithologies (some with glass) that are more likely through analysis to give information on the parental magma compositions (and particularly volatile loads) involved in the formation of the arc. A markedly diverse range of basaltic lithologies was recovered from seamounts located between the back arc and arc axes, including olivine-plagioclase phyric basalts, ankaramatic, and tephritic types, indicative of distinctive parental magma compositions.

The major problem we encountered during the voyage was essentially one of a "shake-down" nature in that SS01/2003 did not use the hydro-winch system. In essence, provided the shake-down for this aspect of the RV Southern Surveyor's systems. In the early parts of our voyage, we encountered a number of difficulties with proper respooling of the CTD wire following reel-outs approaching 3000m during tow-yos. In addition, some mechanical control problems developed with the hydrowinch A-frame and Archimedes screw controlling the respooling feed. We modified the dredging arrangement used by the previous voyage in placing the weights some 2 metres rather than 50 metres above the chain bag, and encountered no problems with this arrangement.

**Voyage Narrative**

The work completed on is presented in the form of a Daily Narrative. completed 70 dredges, 31 tow-yos, 14 vertical hydrocasts, 9 echo-sounding traces, 2 camera tows, and 1 drogue test.

**Day 1. Friday March 14th.** Departed Auckland at 1800 hours, eight hours later than scheduled because of problems with cleanliness of the fresh water tanks. For the next couple of days, we sailed northeastwards to Curtis Island in the Kermadec Group, slowing to allow Cyclone Erica to pass to the north of us. An echosounding traverse (TES-01) was commenced after leaving Auckland. We passed Curtis at 3 am and Macauley at 4.30 am on **Day 4**, **Monday 17th**. From 11 am onwards we could see the much larger island of Raoul ahead. We passed the island on the east side and continued northwards checking the bathymetry for any unknown highs and possible volcanoes. We passed over a number of apparent volcanic structures together with known volcanoes "A" and "Monowai" during the rest of the day and into the morning of **Day 5, Tuesday the 18th March**.

**Possible and known Volcanic Structures north of Raoul Island**

| Structure | latititude (S) | longitude (W) | depth (m) to feature | elevation > sea floor |
|---|---|---|---|---|
| cone | 28° 33.55'S | 177° 39.59' | 700 | 450 |
| double cone | 28° 13.01'S | 177° 33.99' | 935 | 700 |
| cone | 28° 34.46'S | 177° 24.26' | 1310 | 340 |
| cone | 27° 19.83'S | 177° 20.43' | 970 | 300 |
| Volcano A | 27° 12.86'S | 177° 18.81' | 530 | 1370 |
| cone | 26° 23.96'S | 177° 13.92' | 735 | 660 |
| Monowai | 25° 53.20'S | 177° 11.34' | 215 | 1670 |
| cone | 25° 50.09'S | 177° 10.86' | 560 | 310 |
| cone | 25° 45.86'S | 177° 10.17' | 760 | 590 |
| caldera | 25° 25.87'S | 177° 06.64' | 210 | 975 |
| caldera | 25° 12.51'S | 177° 04.50' | 680 | 1035 |
| cone | 25° 09.44'S | 177° 03.89' | 970 | 665 |

**Day 5. Tuesday March 18th.** We arrived at the first station at 1148 hours – a vertical hydrocast about 7 nautical miles south of Volcano 19, to check background hydrochemistry for this southern segment of the Tofua arc: V03B-01 (V: vertical; 03: year; B: second voyage this year for the NOAA team; 01 first vertical hydrocast of TELVE). All the instrumentation of the MINTS sledge and interface with the Surveyor worked flawlessly. We then dredged a flank cone to the SW of Volcano 19: TD-01. Despite difficulties with the readouts for the operation (winch tension based on hydraulic fluid pressure driving the winch not tension on the wire; wire-out is uncalibrated but the Bridge has a correct reading; some drift relative to the preferred dredging direction), the dredge was very successful, returning a full load of black, aphyric, vesicular basalt/basaltic andesite. The technique being adopted on this ship is to commence lowering the dredge while slowly approaching station, aiming to have the dredge on the floor exactly at the station. Then proceed slowly paying our wire at the same rate as the forward motion of the ship, pause at the 2nd waypoint and reel in. Reason for this approach is that the bridge has to manage the entire procedure (control of the ship plus winch) single-handedly. In full dynamic positioning mode, engineers are required full-time in the engine room and this is demanding watch-keeping. Furthermore, the winch operators in the "dog-houses" do not have good tension readouts, requiring the bridge to call out major hook-ups with the dredge.

The first to-yo of the voyage was performed from west to east, initially descending vertically into the centre of the crater of Volcano 19, and then towing eastwards up the wall and down the eastern flank. First volcano and first plumes for TELVE were detected: one ponding about 100m below the lip of the crater at 800 to 1000m depth, and a second weaker plume emanating from the summit "cones" on the eastern flank at 380-400m depth. The second dredge (TD-02) was dragged up the eastern wall of the crater, covering the depth range of the within-crater plume. Aphyric basalt/basaltic andesite, some vesicular and some blocky pillow fragments were recovered in a full bag. Another dredge was immediately performed on the summit of the volcano; recovery comprised hyaloclastite-rich, aphyric basalt/basaltic andesite, about 40% of which is quite strongly oxidised.

The ship was moved to a location between Volcanoes 19 and 18, and a background hydrochemical cast completed (V03B-02), returning to deck at 0035 on Wednesday 19th March.

**Day 6. Wednesday 19th March.** A satellite cone on the east flank of Volcano 18 was the target of TD-04. In a full dredge, two major lithologies were recovered: aphyric, weakly vesicular medium-grey andesite, and plagioclase-phyric, moderately to strongly vesicular dacite. A tow-yo (T03B-02) starting in the crater of Volcano 18 and continuing eastwards up the wall of the crater and across the flanking cone (targeted in TD-04) discovered a plume in the crater (at 920 – 1465m depth) and also at the summit of the flanking cone. The nature of the plume in the crater implies a deep source, possibly from a 50m high mound on the floor.

The next dredge deployed was on the southeast wall of the crater (TD-05), recovering nothing in the main bag and deep chocolate-brown mud with a pumice lump and grit in the closed pipe dredge. We sailed northwest to Stegosaurus (Volcano 18 North), and dredged a cone on the southwestern extension of the apparent rift zone forming the "backbone" of this volcano. Recovery consisted of pillow rim, variably vesicular, black, olivine-microphyric basalt-basaltic andesite in the main dredge bag, and similar hyaloclastitic material in the pipe dredges. In addition, the closed pipe dredge contained mm-sized buttons of native sulfur, and small fragments of hydrothermally-altered rock.

A tow-yo (T03B-03) was initiated at 1218 hours from southwest to northeast along the "spine" of Stegosaurus. No plumes were detected. During recovery of the CTD, a problem with the spooling of wire onto the forward CTD winch became pronounced. The problem appears to be that during initial spooling of this new wire, the tension of the earlier layers is not as high as the outer layers now that some load has been placed on the first-out 1500m of wire. These outer, highly-tensioned layers of wire are biting down into the deeper layers, displacing the symmetry of the rewind and causing uneven spooling. Once the CTD was at the surface, another problem appeared. The hydraulic pump that drives the A-frame for the CTD deployment had been running throughout the long tow-yo operation, had overheated, and seized. After some analysis, it was decided to retrieve the CTD sledge with the main crane – a tricky manoeuvre in moderate sea conditions. Operation terminated finally at 1824 hours with the sledge back on deck.

A conical structure to the northwest of Stegosaurus was the target of dredge TD-07. Mn-oxide-stained pumice was the only material recovered. This structure may be old or alternatively covered with pumice from Volcano 16 to the northeast.

A regional hydrocast (V03B-03) was then completed between Stegosaurus (Volcano 18 North) and Volcano 16, followed by an echosounding transit (TES-02) to investigate a possible dome-type structure shown on the swath-map of the main crater floor of Volcano 16. It became clear that the structure is more likely a slump off the south wall of the crater.

**Day 7. Thursday, 20th March.** It was decided to run a planned tow-yo prior to any dredging, starting in the crater and running out to the northeast; in the event a plume was identified in the crater, the floor would be dredged. In fact the tow-yo (T03B-04) did reveal a plume at 1350 to 1450 m depth. The subsequent dredge (TD-08) on the "dome" on the floor of the crater recovered a couple of pumice boulders in the main bag and foraminiferal sand plus Mn-coated pumice pebbles in the closed pipe dredge. Persisting with this potential hydrothermal target, dredge TD-09 targeted the steep SE wall of the main crater of Volcano 16; weathered, grey, red and white pumice was recovered.

The second of the two tow-yo's (T03B-05) planned for this volcano, offset to the northwest and also striking SW-NE was then completed. This tow traversed another crater in which a slight increase in particles was detected at 900 to 1000m depth; this may be hydrothermal in origin, but no stronger "above-bottom" plume (consistent with buoyant rise) existed. A dredge (TD-10) on the peak of the NW summit of Volcano #16 recovered quartz-amphibole-orthopyroxene-bearing pumice characterised by extremely stretched vesicles.

The next regional background cast (V03B-04) was completed between Volcanoes 16 and 15 followed by a dredge (TD-11) on the peak of the SW dome of Volcano 15. Pebbles and cobbles of strongly vesicular quartz-orthopyroxene-phyric, Fe-stained white pumice were recovered in the main bag together with chocolate brown mud in the closed pipe dredge. A tow-yo (T03B-06) across the summit crater of Volcano 15 revealed no plumes.

**Day 8. Friday 21st March.** Although the next dredge (TD-12) on the crest of the ridge NE of Volcano 15, was executed flawlessly under very trying conditions, no samples were recovered. Wind and chop superimposed on 4m swell coming from $120^0$ made dredging life difficult. The lead weight was also damaged with a substantial crack below the eye-hook, and requires some welding repair.

Regional hydrocast V03B-05 was completed between Volcanoes 15 and 14 followed by a dredge (TD-13) on the southwest flank of Volcano 14. Weak to moderate Fe-stained, streaky white pumice with microphenocrysts of orthopyroxene was recovered. After a false beginning during which the ship drifted away from the first dip point requiring a restart of the operation, a tow-yo across the twin-cratered summit of Volcano 14 detected a plume at 940 to 980 m depth in the western crater and no sign of activity in the older eastern crater. So far therefore, 4 out of the 6 volcanoes studied have one or more plumes associated with them.

A dredge (TD-14) on the inner SSE wall of the western crater of Volcano 14 recovered a full bag with a variety of mafic (olivine-plagioclase-phyric) and felsic (feldspar-phyric) volcanic rocks, a plagioclase-rich gabbro and a minor proportion of sulfide-rich feldspathic lithologies. We transited NNE into territory that had not been swath mapped by the Sonne, to check on the possibility of a missing volcanic edifice, and in the absence of such a structure to complete the next regional hydrocast (V03B-06). A greater depth of $H_2O$ was also desired to run off and re-spool the hydrowire. No edifice was discovered and so V03B-06 was completed. An echosounding trace (TES-03) continued from the hydrocast site to check whether any other volcanic edifices existed prior to encountering the known structure located south of Volcano 8 (Pelorus) at about $22^o$ 59.2'S. Again no edifice was detected, so the comparatively lengthy portion ( about 20 nautical miles) of the Tofua arc with no volcanoes between Pelorus and Volcano 14 appears to be a real feature.

**Day 9. Saturday 22nd March.** After an echosounding search had been run to locate the summit, dredge TD-15 was completed on the northwest flank. About 20 pebbles/cobbles of old-looking, dark grey to pale brown, quartz-phyric pumice with stretched vesicles were recovered. A north-south tow-yo (T03B-08) across the summit area of Volcano 8, east of the shallow ground forming the "Pelorus Reef", discovered a hydrothermal plume at 200 m depth. A dredge (TD-16) to sample the inferred source of this plume on the eastern flank of the volcano returned a full bag of aphyric, scoriaceous basalt ranging from fresh to coral-encrusted. The pipe dredge was full of black-grey basaltic sand. Another dredge (TD-17) targeting the western upper flanks of Volcano 8 recovered variably vesicular, plagioclase-phyric black basalt/basaltic andesite; some of this material had rims of palagonitised glass.

Between the Tofua arc front and the Valu Fa Ridge, the Smith and Sandwell gravity maps and available bathymetry indicate a number of conical, apparently volcano-like features. We attempted to locate one of these using the gravity map alone in the absence of swath bathymetry. The echosounding trace discovered a single large structure at about 22° 40.9'S 176° 30.94'W. In retrospect, we should have become alert to the possibility of some navigational problems stemming from the use of a transparent overlay on the Sonne bathymetry to guide the echosounding exercise. Nevertheless, a single volcanic edifice with a summit at about 1250m was located ("K1"), and a dredge (TD-18) completed on the northwestern flank. In a _-full dredge bag, some fresh glass-rimmed, variably but markedly olivine-clinopyroxene-plagioclase phyric pillow rim basalt fragments were recovered, together with 2 blocks of quartz-phyric pumice.

Continuing our search for volcanoes further west of K1, an echosounding trace (TES-05) detected no others; in fact, a depression rather than any topographic highs was the result of this effort. So a tow-yo across the summit of the distinctively conical K2 was planned (T03B-09), and partially executed. But at this stage, in the absence of the expected bathymetry given the available Sonne data, the navigational error with the overlay became obvious: a misplacement by 1' to the east. Accordingly, T03B-09 was aborted, and a new to-yo (T03B-10) across the correctly located summit at 22° 41.80'S 176° 36.00'W was completed. No plumes were discovered.

A SSE-directed dredge (TD-19) towards the summit of K2 recovered just a few chips of black basalt/andesite in the closed pipe dredge. Not much tension had been noted during the hauling-in. Rather than proceeding to another seamount, it was decided to repeat the dredge (TD-19R) with the modification of letting more wire out once the ship had reached the first waypoint, and more during the transit to the second waypoint. The result (an excellent haul of fresh, glassy-rinded, black, variably vesicular basalt/andesite) perhaps confirms the sense on the Surveyor of paying out plenty of wire.

The first of several planned tow-yos (T03B-11) along-strike of the Valu Fa Ridge occupied much of the night shift. The tow was along the southernmost, actively spreading segment of the Ridge.

**Day 10. Sunday 23rd March.** No plumes were detected along the 15 nautical mile length of T03B-11. A series of dredges along the length of this southernmost segment of the Valu Fa were then completed, with emphasis on the southernmost, propagating tip. The first of these series (TD-20) targeted the highest point of the northernmost part of the southern segment of the Valu Fa Ridge, and recovered about 40 kg of fresh, vescicular, vitrophyric pillow rims and interiors, and substantial amounts of rock chips, grit, and mud in the pipe dredges. Judging on the satiny (possibly feldspar-microphyric) appearance of the glass, much of this material could be andesitic/dacitic in composition. In sequence these dredges (with haul-point latitudes) were:

TD-20 22° 30.95' S (lithologies, as above)
TD-21 22° 33.60' S black, glassy, variably vesicular andesite/dacite with "woody" flow tops.
TD-22 22° 37.90' S empty dredge bag, but black basaltic (? or andesitic) grit plus a spectacular xenolith-bearing andesite in the pipe dredge.
TD-23 22° 41.80' S fresh, black, glassy, vesicular dacite.
TD-24 22° 43.65' S weakly vesicular pillowed basalt/ andesite with glassy rinds, plus 2 felsic pumice fragments.

**Day 11. Monday 24th March.**
TD-25 22° 42.82' S black, aphyric, vesicular pillowed dacite with very glassy rinds.
TD-26 22 ° 39.52' S a torso-sized boulder and _ dozen fist- to head-sized cobbles/boulders of aphyric, black, weakly vesicular dacite. Some of this material appears to be pepperite.

A very interesting feature of a number of the material recovered in a number of these dredges was occurrence of disseminated, very pale green (and presumably Mg-rich) olivine. In a few, clots of strongly vesicular, grey, olivine-plagioclase-phyric basalt are present hosted by dense, black glass of presumably more felsic composition.

The dredging technique used by the Surveyor again worked very well on the topography of the Valu Fa Ridge. For example, TD-24 sampled the floor of an apparent graben at the southern tip of the Ridge. The key requirement for these depths and targets seemed to be at least 300m wire out over waypoint separations of some 250m.

With completion of this dredge series, the next of the tow-yo series (T03B-12) along the second segment of the Valu Fa was completed. This segment includes the active hydrothermal field of Hine Hina. While only a very weak plume was detected at Hine Hina, much stronger new plumes were detected along the northern part of the tow (22° 30.8' to 22 ° 27.5'S). Both thermal (DT = 0.009 °C) and light scattering (~0.02 mV) anomalies were present. Some signals were near bottom (>2000m) at 22° 28.5' to 29° S, and an above bottom (~1850m) signal was present to the north of this. The chronic problem of CTD winch wire wrapping delayed the return of the MINTS to deck by 1.5 hours.

With completion of the second Valu Fa tow-yo, another series of dredges along this second segment commenced. A couple of these targeted the thermal anomaly detected by the tow-yo. Another was hauled through the Hine Hina area. The dredge sequence was interrupted by an attempt to spool off all the forward CTD winch wire (7 km) and test a drogue performance. An accident during this exercise occurred to the Bosun. A block being used to direct the wire aft through the starboard trawl, jerked and hit the Bosun in the head. The spooling was terminated. After first aid and careful consideration and monitoring of the patient's condition through the night, dredging recommenced. Recoveries were dominated by glassy andesite/dacite, with specific results as follows (with haul point latitudes):

TD-27 22° 28.43' S fresh, black, aphyric, glassy, weakly vesicular dacite. Some "woody" pumiceous flow-top material.
TD-28 22° 30.70'S black, glassy, weakly to moderately vesicular aphyric dacite; about 10% showing dull brownish alteration. Orange hydrothermal Fe-Si-oxyhydroxide crusts cement glassy dacite grit in the closed pipe dredge.
TD-29 22° 32.00'S fresh, black, glassy, aphyric, weakly vesicular dacite; minor surficial sulfate bloom, and some Fe-Si-oxyhydroxide crusts.

**Day 12. Tuesday 25th March.**
TD-30 22° 35.60'S fresh, black, glassy, moderately vesicular, aphyric dacite.
TD-31 22° 36.70'S pipe dredge full of glassy dacitic grit.
TD-32 22° 37.75'S fresh, black, glass-crusted dacite.
TD-33 22° 38.15'S fresh, black, aphyric, glass-encrusted dacite.
TD-34 22° 28.68'S fresh, black, aphyric, glass-encrusted dacite.
TD-35 22° 27.75'S stripey, black, variably fresh to altered (grey) dacite; minor proportion is low-density, pumiceous grey dacite.

Following this sequence of dredges along the central portion of the Valu Fa Ridge, a return was made to the nominal position (22$^{o}$ 32.0'S 176$^{o}$ 43.05'W) of the Hine Hina field to complete a vertical hydrocast. This cast was made to assure ourselves that the hydrothermal activity at Hine Hina was undetectable with >20m above-sea-floor $H_2O$ sampling; the result confirmed a complete absence of activity.

**Day 13. Wednesday 26th March.**
Another two-yo (T03B-13) occupying 14 hours, along the Vai Lili segment of the Valu Fa Ridge then commenced. Weak thermal anomalies were detected along much of the segment, but really strong plumes were encountered north of the reported position of Vai Lili. In addition, at the northernmost end of the tow, a plume at 1400 to 1460m depth could be emanating from a seamount at with a summit at about 1700m depth.

There was some concern with the bosun's loss of sensation to the upper left part of his skull. To avoid having gear in the water while a decision was made about his condition, and a possible trip to Nuku'alofa, an echosounding traverse was executed to a volcanic cone about 10 nautical miles to the west of the Valu Fa Ridge. We had identified a series of off-ridge axis cone targets, and this one (called K9 with the voyage's numbering system) is the furthest west for our dredging campaign.

With the summit region defined, a dredge (TD-36) was completed on the northwestern flank which returned orthopyroxene-microphyric, white streaky pumice. This material most likely is derived from the Tofua arc and is blanketing a relatively old cone whose constituents were not sampled.
We backtracked to another off-axis cone (K8) in the vicinity of the overlapping Vai Lili and Northern (White Church) segments of the Valu Fa Ridge, and completed dredge TD-37. This time in addition to fresh white pumice, older pillow lava fragments were recovered. A tow-yo (T03B-14) running towards ESE and crossing the axis of the Valu Fa Ridge through the centre of the most intense thermal anomalies identified on the along-axis tow, was initiated at K8 heading towards a cone (K10) on the eastern side of the Ridge. Unfortunately, the wind was blowing the ship onto the CTD wire on this heading and the tow had to be terminated. During the initial stages of this tow over Volcano K8, no plume was detected. Despite the wind and current, vertical hydrocasts were possible so V03B-08 was deployed at the Mariner anomaly identified during the T03B-13. At the particular location of the hydrocast, the plume was not as intense as that identified during the tow-yo with no eH anomaly and a lower thermal anomaly.

**Day 14. Thursday 27th March.**
Two camera tows were then attempted along the axial strike of the Ridge through the location of the most intense Mariner plume. The first of these (TV-01) was aborted because the ship had to be kept moving southwards away from the first (vertical drop) waypoint to avoid the wire fouling the prop. The second attempt was also terminated after a few minutes because the bottom-return signal from the pinger could not be detected; the camera cage had moved too far to port, outside of the acoustic reception footprint of the ship. Upon recovery, a few minutes of video revealed a sandy sedimented bottom with a few pillows, and a small chimney emitting clear fluid.

Our luck did not improve as the next dredge (TD-38) targeting the region of the Vai Lili field, recovered nothing despite several good tension spikes. A hydrocast (V03B-09) was deployed at Vai Lili and confirmed relative quiescence with weak nephelometer and DT readings in the bottom 100m, and no plume layering. The next dredge (TD-39) at the Si'iSi'i venting area to the south of Vai Lili recovered fresh dark grey, aphyric,moderately vesicular dacite, but the planned hydrocast (V03B-10) could not commence due to a problem with the CTD winch. During this delay, we transited to the south to deploy a dredge in the central part of the Vai Lili segment of the Ridge but discovered the problem with the CTD winch was general to the ship's winching systems. The problem was rectified and the dredge (TD-40) undertaken. Nothing was recovered but rather than repeat the dredge we decided to move to the next location southwards, at the southern crest of the Ridge. This dredge (TD-41) recovered black, shiny, glassy,aphyric dacite, as did the next dredge (TD-42) at the southern termination of the Vai Lili segment. The first minor damage to the dredge configuration occurred during this dredge: the grill at the bottom of the "open" pipe dredge had been ripped off.

Renewed problems with the forward CTD winch wrap-on forced a delay in returning to deck for the next operation, a hydrocast at the Misiteli plume. The cast did however, confirm a similar structure to the plume as recorded during T03B-13.

At this stage, it was decided to move eastwards to sample more of the seamounts lying between the arc front and the Valu Fa Ridge. During the deployment of TD-43 at Seamount K15, one of the twin weights at the head of the dredge was pulled back through the block, while the other was sheared off and fell into the sea. After replacing this weight, the dredge was successfully finished, recovering relatively old-looking, black plagioclase-phyric basalt. Recovery of Mn-coated, moderately vesicular, aphyric, glass-crusted pillow fragments together with bedded silts and sands from the next seamount target (K12) east of the Valu Fa by dredge TD-44 also indicated an old (volcanically-inactive) structure.

**Day 15. Friday 28th March.**

The ship was moved back to the Vai Lili segment of the Valu Fa Ridge, and the region in the vicinity of the Mariner's plume was targeted during the next two dredges (TD-45; TD-46). In large loads, the first dredge recovered black,aphyric, vesicular basalt/dacite (?) cinder blocks, many encrusted with glass and some with ropey textures. Rare greyish tan surface alteration was present on some blocks. The second dredge recovered similar material: black, fresh, glassy aphyric, weakly vesicular dacite; some 10% of the material was pale grey-blue possibly from a surface sulfate sheen, and 5% was medium grey and apparently pervasively altered.

The next major target was the White Church segment of the Valu Fa Ridge commencing with a tow-yo (T03B-15). This had to be aborted shortly after launch with an electrical connection failure. The MINTS was returned to the surface, and it became clear that a re-termination of the CTD wire was required. While this was taking place, the time was constructively used by completing the dredges along the length of the Vai Lili segment with a final dredge (TD-47) at the northernmost end of this portion of the ridge. A full load of black, fresh,glassy dacite plus some ropey-textured lavas was recovered, together with a few blocks of pumice.

The second tow-yo attempt (T03B-16) of the White Church segment again failed, this time due to the failure of a component in the mechanical system guiding the spooling. With MINTS returned to deck, the repair period was used to deploy two dredges: the first of these (TD-48) was at the southern termination of the White Church segment (black, fresh, glassy, moderately vesicular dacite recovered), and the second (TD-49) at the summit of Seamount K11 to the east of the Valu Fa Ridge (boulders and cobbles of Mn-Fe oxide-coated, mega-clinopyroxene-phyric, olivine-bearing, vesicular basalt (80%) and semi-indurated sandstones (20%) obtained).

The third attempt to tow-yo the White Church segment (T03B-17) once again had an inauspicious start. The MINTS was in the water at 1916, stopped at 1918 with loss of power, restarted at 1937 and stopped at 2003 with a problem in the "remote control". The problem was fixed at 2152, and the tow-yo proceeded finding numerous small (in terms of thermal, nephelometry and Eh) but no major plumes along the segment as far as 22$^{o}$ S.

**Day 16. Saturday 29th March**

With T03B-17 back on deck at 0758 hours, an echosounding transit (TES-07) was run to locate the summit of Seamount K6. This prominent cone is located at the northern end of the Vai Lili segment of the Valu Fa Ridge, and could be a possible source of the ~ 1400 m depth plume detected on the tow-yo along this segment, and perhaps a propogating northern tip of the Vai Lili segment. It became clear during the course of the tow-yo along the White Church segment, that the true location of topographic features are about 1 km south of their positions as plotted on the RV Sonne SO48 chart. With the summit of K6 located, a dredge (TD-50) from NW to SE was run towards it; surprisingly, despite a completely normal deployment and tension plot, only faint smears of foraminifer-bearing light tan mud on the frame of the dredge was recovered.

In order to clarify the distribution and sources of the variety of plumes that had been detected at the northern end of the Vai Lili and southern end of the White Church segments of the Valu Fa Ridge, another tow (T03B-18) was run orthogonally to the axial terminations of these segments. The tow-yo commenced at 1315 and was out of the water at 1850, deployed in excellent weather at last: bright sunshine, low swell and sea, and the island of Ata clearly visible to the east. During the course of the tow, the ship was moving through what looked like a "coral spawn bloom" with a pair of metre-long, irridescent Mahi Mahi ("Dolphin Fish") accompanying the ship for a couple of hours. Given the calm sea state, we decided to re-try towing the video camera along the Vai Lili segment in the region of the Mariner plume. The tow was excellently executed and about 80 minutes of good photography were obtained: remarkably rugged, jumbled, angular blocks of glassy dacite with persistent light dusting to apparently heavy accumulations of sediment, and not much evidence of life were visible. Although the Mariner Plume was detected by the on-camera sledge CTD, no sign of proximity to hydrothermal venting was seen on the video.

Another tow-yo (T03B-19) was then deployed (in water at 2325 hours) across the southern end of the White Church segment towards Volcano K6, in order to explore the complex plume distribution in this region more fully.

**Day 17. Sunday 30th March.**

With T03B-19 out of the water at 0317 hours, another attempt to dredge the summit region of Volcano K6 commenced. This time the dredge (TD-51) was successful with a full dredge bag comprising fresh, vesicular, plagioclase-olivine-phyric, glass-encrusted pillow fragments. Some of the rock pieces had a grey-cream brown surficial staining on fractures, and similar colouration in a more pervasive alteration of pillow margins. The White Church segment of the Valu Fa Ridge was then dredged (TD-52) in the region of a nephelometer and thermal anomaly, and at the same latitude (22$^{o}$ 10'S) as the off-axis volcano K6. In a full dredge bag, two types of shiny black, fresh dacite and three different types of vesicular andesite were recovered together with some white pumice. The latter is a ubiquitous feature of all the dredge recoveries along the Valu Fa Ridge, and is presumable derived from the Tofua arc, some 40 to 50 km to the east.

We had been systematically trying to recover samples from seamounts located between the Valu Fa Ridge and the Tofua arc. This campaign continued as we headed back southwards towards Volcano 7 in the arc, by tackling a series of these seamounts, with the first being K10 (TD-53), located at the end of one of the cross-Valu Fa-strike tow-yos (T03B-18). A full dredge bag of plagioclase-clinopyroxene-phyric pillow basalt/andesite with moderately fresh glassy rinds, and vesicularity varying from poor to strong, was recovered together with some white pumice.

A dredge on the next seamount target ( K13) recovered nothing on the first attempt (TD-54), and merely a few pillow basalt rinds and cobbles on the next (TD-55) despite strong tension spikes in excess of 6 tons. The chain bag had a number of holes in it on recovery from this effort, and rocks were observed falling through the bag during the haul onto the deck. The lithologies from this large seamount appeared to be older than those closer to the Valu Fa Ridge. After repair of the bag, a similar meagre recovery of weathered pillow basalt rinds resulted from the following dredge (TD-56) on K14. Some of this material was olivine-clinopyroxene-phyric (presumably basalt) while other cobbles were plagioclase-phyric (probably andesite).

During the 12 nautical mile sail southwards from the TD-56 site to the start of the first tow-yo at Volcano 7, we tested (to destruction) from a standing start, the drag characteristics as a function of flow speed of a 12' parachute-style drogue produced by Sea Anchors Australia®. The shrouds failed at about 4.5 knots, and the drogue was recovered. We arrived at the southernmost edifice (7a) of Volcano 7 and ran a tow-yo (T03B-20) across its flanks and crater. No plume was detected. A dredge (TD-57) of the northern wall of this crater recovered only a small load despite some strong, sustained pulls (in excess of 6 tons). Nevertheless the material recovered included olivine-phyric basalt together with the usual pumice.

**Day 18. Monday 31st March.**

A tow-yo (T03B-21) across the second major edifice (7b) of Volcano 7 also failed to detect any plumes. A dredge on the crest of a 700m high conical feature to the northwest of 7b experienced pulls of 11 and 9 tons, but did not break the weak link and recovered a full load of plagioclase-phyric pillow basalt with glassy, oxidized rinds, a slab of volcaniclastic sediment and minor amounts of white-grey pumice. A relatively small structure between Volcanoes 6 and 7 mapped by SO167, and herein called Volcano 6.5, was the target of the next tow-yo (T03B-22). A plume at 700 m depth (maximum light scattering anomaly of 0.017 mV) with a thickness of ~ 100 m was detected over much of the tow. A dredge of the summit region of Volcano 6.5 recovered only a few pebbles of weathered, but petrologically-useful olivine-clinopyroxene-phyric basalt.

Given the evidence of SO167 swath maps, we decided not to invest time in investigating the apparently relatively old, degraded structures of Volcanoes 6 and 5 and moved to the triple edifices comprising Volcano 4. A tow-yo (T03B-23) over the northwest edifice which includes a crater detected no hydrothermal plume. Dredging (TD-60) of the large cone at the northern end of this edifice recovered a large load of boulders and cobbles, including abundant grey-white pumice, volcaniclastic sandstone, olivine-pyroxene-plagioclase-phyric basalt, and a flow-banded, vitrophyric-looking, feldspar-phyric lava or tuff.

On the Smith and Sandwell gravity map, about 4 nautical miles to the west of Volcano 4, a structure apparently of comparable size to volcanoes K1 and K2 can be seen. We lacked good swath bathymetry for this region, but decided to search for this possible "off-axis" volcano. A cratered summit (crater floor at 22 05.02'S 176 21.90'W) was detected but given its relatively small size, we decided not to proceed with any dredging or CTD work, and return to the other edifices of Volcano 4. A tow-yo (T03B-24) was initiated at 2350 hours over the North edifice.

**Day 19. Tuesday 1st April.**
No plumes were detected on the North edifice of Volcano 4, and the CTD was out of the water at 0142 hours. Rather than dredge the summit, an attempt to recover samples from a small cone to the southwest of the main structure was made (TD-61). The dredge got hung up more or less at the drop point for about 40 minutes, but was eventually recovered with _ bag-full dominated by a conglomeratic lithology consisting of Mn-oxide cemented pebbles of volcanic rock. Minor proportions were present of semi-lithified, tan siltstone, dark brown/black volcaniclastic sandstone, and Mn-encrusted weakly plagioclase-phyric vesicular lava.

The next tow-yo (T03B-25) over the summit region of Volcano 4 (South) detected a particle plume at about 100 m depth, but until the on-shore chemical analyses are completed, it is not certain if this is from the near-surface biota or hydrothermal in origin. A dredge (TD-62) pf the northwestern summit flank of Volcano 4 (South) recovered glass (mostly devitrified)-encrusted, plagioclase-phyric andesite/dacite with ropey surfaces. The flow interiors were highly vesicular, frothy black glass.

We moved back eastwards to Volcano 5, most of which seems to be formed of old, wave-base planed eroded structures. A tow-yo (T03B-27) across the morphologically younger-looking cone of 5 (South) detected a possible plume at 780 m depth, but a navigational problem caused the early termination of this tow to be followed immediately by a vertical cast (V03B-11) at the summit to sample a particle plume at about 580m.

A dredge (TD-63) of the northwestern summit region of Volcano 5 (South) got hung up with tensions in excess of 13 tons; the weak link was slightly bent on recovery. The haul consisted of fist-to-head sized blocks of bottle-green clinopyroxene-plagioclase-phyric basalt/andesite with thin, and mostly altered glassy margins. We traversed northwards to the adjacent volcanic complex of Volcano 5 (North), and ran a tow-yo (T03B-28) across the summit region which detected a plume that was strongest over the summit itself. A dredge (TD-65) of this summit region recovered a _ -full bag of dirty grey-brown pumice and black, slabby, manganiferous crusts with embedded grit. A galatheid was found living in a hole in one of these slabs.

**Day 20. Wednesday 2nd April.**
A background hydrocast (V03B-12) between Volcanoes 3 and 5 was completed, followed by a dredge of the summit region of Volcano 3. A full bag containing two types of rock was recovered: pale grey pumice, and a dull, dark grey aphyric vesicular dacite. A tow-yo (T03B-29) across the summit region of Volcano 3 detected no plumes, and was followed by a background hydrochemical cast (V03B-13) between Volcanoes 3 and 2.

During the transit northwards from the background cast station towards Volcano 2, a sharp conical feature (crest 400 m deep, we named Volcano 2.5) was noted in a gap in the SO167 bathymetric coverage at 21° 22.97'S 175° 44.88'W. We returned to this feature having completed a vertical hydrocast over the summit of Volcano 2 (no plumes detected), running an echosounding trace (TES-09) to locate its summit. Relatively old olivine-clinopyroxene-plagioclase-phyric, non-vesicular basaltic andesite was recovered from the northwestern summit flank in dredge TD-66.

Finishing with a major flourish, we discovered strong plumes in the caldera of Volcano 1 during tow-yo T03B-30. One source is likely to be at the base of the caldera wall at a depth >400m. A second stronger source is at the base of a volcanic construct on the western ridge of the caldera. This region was targeted in dredge TD-67; recovery was mostly weakly to very vesicular, aphyric to plagioclase-phyric lavas, possibly varying from dacite to basaltic andesite. About 10% of the full load was volcaniclastic with pervasive grey-green, chlorite-smectite alteration with rare quartz amygdules, and minor amounts of pyrite in the volcaniclastic cement. This dredge was followed by another (TD-

68) offset to the south by about 50 metres and following a parallel track to TD-67. Similar lithologies were again recovered with about 50% altered rocks including some with chalcopyrite-quartz-bearing veins.

In order to narrow down the plume distribution within the caldera further, a tow-yo (T03B-31) running NNW at an angle to the earlier tow was executed, and successfully identified an area of the western ridge of the crater as the source of a very strong plume, with a density anomaly at 21° 09.45'S 175° 45.0'W, 172m depth. A dredge (TD-69) run through this zone recovered glassy, variably vesicular to massive, aphyric lava. A minor proportion of altered volcanic rocks were present in both the chain bag and the pipe dredges. The final dredge (TD-70) of SS02/2003 targeted the zone between TD-68 and TD-69, and recovered a small haul of material similar to that obtained in preceding dredge. The operation was on the after deck at 2339 hours, in time for the deadline set of midnight to cease science operations.

While laboratory work continued on the samples recovered in the preceding few hours, the RV Southern Surveyor headed for Nuku'alofa, arriving on schedule at 1000 hrs on Thursday, 3rd April.

**Summary**

The voyage to the Tonga-Eastern Lau Basin region successfully accomplished its major objectives comprising a study of the hydrothermal plume activity of the Tofua Arc and adjacent Valu Fa back arc Ridge, coupled with recovery of sea floor volcanic rock samples.

Despite the extremely limited time made available prior to departure from Hobart in terms of fitting out the ship for the type of scientific program planned for TELVE, we completed the majority of an ambitious and pioneering research program.

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Peter Graham, Chief Cook

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Graham McDougall, Bosun
Allan Brownlie, IR
Fred Germann , IR
Rebecca Brown, IR

Phil French, Engineer IR
The success of the voyage was a direct function of the expertise, enthusiasm, sustained energy, and willingness to try new techniques of the RV Southern Surveyor's crew. A highly competent and flexible trio of experts from the CSIRO, working under considerable stress, sustained the ship's scientific systems, and provided excellent liaison with the ship's crew. A combination of dual, temporally dove-tailed, but labour-intensive scientific programs (hydrochemical and petrological) resulted in a very efficient use of the ship's time. But the limited space for scientific staff aboard this vessel consequently meant considerable strains were imposed on the nine scientific staff. They coped with this load to produce outstanding and exciting results which are a prelude to on-shore, intensive laboratory studies.

We are grateful to the Kingdom of Tonga for granting us permission to conduct this research in their waters. Mr Rennie Vaiomo'unga of the Tongan Ministry of Lands, Survey and Natural Resources not only acted as the Kingdom's official observer for the voyage, but also participated fully in the scientific work, particularly the water sampling aspects.

**Richard J. Arculus**
**Chief Scientist**