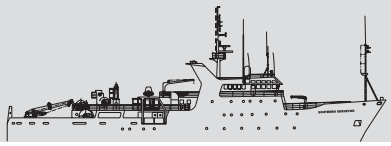

MARINE
NATIONAL FACILITY

2004 program

RV *Southern Surveyor*

CSIRO

voyage summary SS11/2004

SS11/2004

NoToVE-2004 (Northern Tonga Vents Expedition)
Submarine hydrothermal plume activity and petrology
of the northern Tofua Arc, Tonga.

Itinerary

Departed Nuku'alofa 1000 hrs, Wednesday 27 October, 2004
Arrived Apia 0900 hrs, Tuesday 16th November, 2004

Principal Investigator

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Scientific Objectives

1. We proposed to extend the same successful plume-location/characterisation approach used on the SS02/03 voyage in the southern Tofua arc, northwards along the strike of the arc to its northern termination. With increasing rates of plate convergence in this direction, the obvious hypothesis to test was whether an increase in mass flux manifest by the intensity (frequency of centres and scale of plumes) of hydrothermal plume activity exists.

2. The second major objective was to recover fresh glassy rock samples for detailed chemical analysis, particularly of volatile elements and compounds, and stable isotopic characteristics. This effort complements the samples recovered during the SS02/03 voyage, that are now being analysed. Our overall primary objective with these (glassy) rock samples is to quantify the volatile fluxes in supra-subduction zone settings, and attempt to distinguish the components involved (mantle wedge, subducted crust, overriding arc lithosphere).

3. Recovery of massive sulfides which will be analysed for their geochemical signatures including isotopes to characterize the chemical conditions of ore formation.

Voyage Objectives

1. To perform the first detailed, high-resolution, swathmap bathymetric surveys of individual submarine volcanoes of the northern Tofua Arc between 20o 50'S and 15o 20'S, using the Kongsberg EM300 system;

2. To perform the first detailed, high-resolution swathmap bathymetric survey of the Fonualei Rifts, a nascent backarc basin immediately adjacent and northwest of Fonualei;

3. Dredge igneous rock targets identified on these submarine volcanoes, and the floor of the Fonualei Rifts, in order to recover fresh glassy rock samples for detailed age studies and chemical analysis, particularly of volatile elements and compounds, radiogenic and stable isotopic characteristics.

4. Dredge hydrothermal sulfide-rich and altered rock samples for studies of base and precious metal mineralisation;

5. To explore with the transmissometer/nephelometer-equipped CTD sledge for hydrothermal plume activity in these volcanoes and rifts, and to recover water samples for immediate analysis on board and subsequent shore-based laboratory analysis.

Table 1. Coordinates (centres of survey areas) of Specific Targets

Area		Latitude	Longitude
A		20° 50'S	175° 32'W
B	Hunga Ha'apai	20° 35'S	175° 22'W
	Fonua Fo'ou	20° 20'S	175° 22'W
C		20° 08'S	175° 09'W
D		19° 27'S	174° 55'W
E	Metis Shoal	19° 12'S	174° 50'W
	Home Reef	19° 00'S	174° 47'W
F		18° 30'S	174° 20'W
G	Fonualei	18° 02'S	174° 20'W
H		17° 52'S	174° 15'W
I		17° 35'S	174° 10'W
	Fonualei Rifts centred at	17° 35'S	174° 30'W
J		17° 10'S	173° 50'W
K		16° 40'S	173° 40'W
L		16° 20'S	173° 55'W
M	Tafahi	16° 51'S	173° 43'W
N	Curacoa	15° 35'S	173° 40'W
O		15° 20'S	174° 00'W

Voyage Track

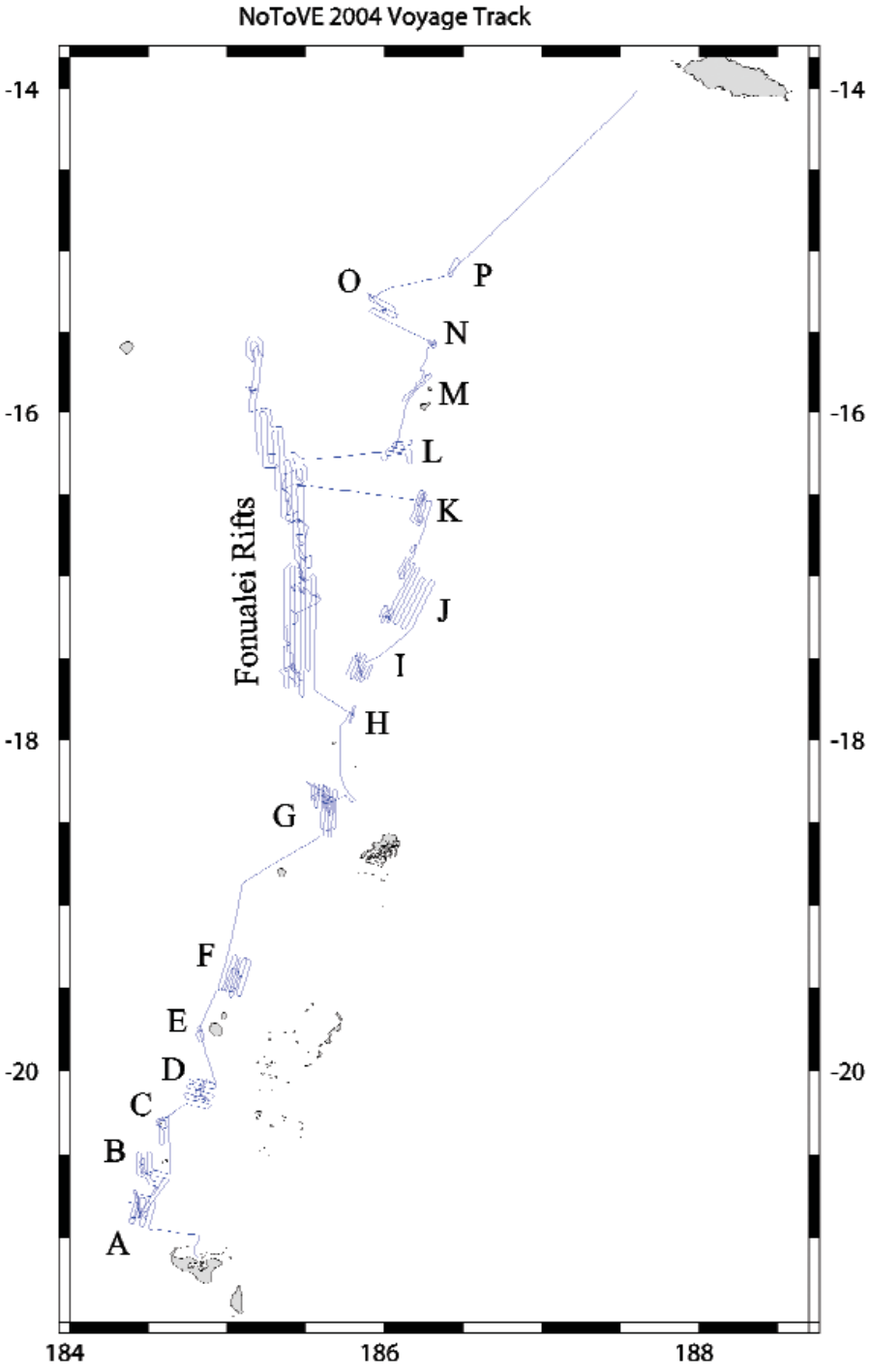

Figure 1. Voyage track of RV Southern Surveyor voyage SS11/2004 (NoToVE), showing the primary areas of operations. Departure was from Nuku'alofa and the endpoint in Apia.

Results

Results of the *NoToVE* SS11/2004 exceeded the expectations outlined in the voyage plan with 74 dredges, 19 hydrocasts, 2 grabs, and much more extensive areas ensonified than planned of the backarc Fonualei Rifts in particular. In summary, the results reported against the specific voyage objectives were:

1. *It is proposed to extend the same successful plume-location/characterisation approach used on the SS02/03 voyage in the southern Tofua arc, northwards along the strike of the arc to its northern termination. With increasing rates of plate convergence in this direction, the obvious hypothesis to test is whether an increase in mass flux manifest by the intensity (frequency of centres and scale of plumes) of hydrothermal plume activity exists:*

Our standard approach to the volcanic targets was to swath map the areas and then on the basis of the ensonified images (both bathymetric and acoustic backscatter) to select targets for hydrocasts and dredging. Using this approach, we found several of the volcanic centres of the northern Tofua Arc are hydrothermally active. However, a major discovery of *NoToVE* is the fact that the nascent Fonualei Rifts have captured the total supra-subduction zone magmatic flux between the latitudes defined by Targets H to K. And numerous, complex hydrothermal plumes were identified in the Rifts. Sampling of all of these plumes for laboratory analysis of 3He and dissolved metals was carried out.

2. *The second major objective is to recover fresh glassy rock samples for detailed chemical analysis, particularly of volatile elements and compounds, and stable isotopic characteristics. This effort will complement the samples recovered during the SS02/03 voyage, that are now being analysed. Our overall primary objective with these (glassy) rock samples is to quantify the volatile fluxes in supra-subduction zone settings, and attempt to distinguish the components involved (mantle wedge, subducted crust, overriding arc lithosphere):*

Spectacularly glassy rock samples were recovered from both arc and backarc volcanoes and ridges. Macroscopic optical studies suggest the majority of these samples are basalts with a minor proportion of dacite and rhyolite. Many of the mafic samples include micro- to strongly porphyritic (with olivine) types.

3. *Recovery of massive sulfides which will be analysed for their geochemical signatures including isotopes to characterize the chemical conditions of ore formation:*

While a limited proportion of hydrothermally altered rocks were retrieved by dredging of a number of the arc and backarc environments, the most spectacular retrieval of massively altered and sulfide-bearing lithologies was from Target O.

Voyage Narrative

Day 1. Wednesday October 27th. Departed Nuku'alofa at 0958 hours, after less than 16 hours in port. Leaving the Tongatapu lagoon, we traveled northwestwards towards "Target A", identified by bathymetry and satellite gravity as the next possible volcanic structure north of "Volcano 1" in the Tofua Arc that was mapped and sampled during the RV *Sonne* 167 (late 2002) and TELVE (SS02/2003) voyages.

Swath mapping continued through the rest of the day and into the early hours of the next, revealing a double cone structure – a simple cone rising to ~ 50m below sea level in the south and a cratered cone to the north. Small cones are distributed along a NNW-SSE-striking lineament through these two major features.

Day 2. Thursday October 28th. A vertical hydrocast (NH-01) into the crater (20° 47.447'S, 175° 33.733'W) of the North Cone was the first operation of *NoToVE*, commenced at 0340 hours; in part, this was to check out the proper operation of the CTD and the newly-installed transmissometer. All systems functioned perfectly on a 900m-deep cast. No hydrothermal plumes were observed but 9 niskin bottles were sampled to establish a pH and dissolved metal profile.

A dredge (ND-01) of the east wall of the North Cone crater recovered somewhat old-looking columnar jointed blocks and boulders (variably altered) of olivine-clinopyroxene-plagioclase-phyric basalt or basaltic andesite. Glomerocrysts of olivine up to 2 cm in diameter were observed. Fresh, glassy-rinded, sparsely olivine-clinopyroxene-phyric basalt was dredged (ND-02) from a satellite cone to the south of the North Cone crater and spectacularly olivine-phyric, black, vesicular, glassy basalt was dredged (ND-03) from a satellite cone on the northern flank of the South Cone.

Further swath mapping to the northeast (towards the islands of Hunga Ha'apai and Hunga Tonga) of Target A revealed another cluster of 3 volcanic structures. We swung back to dredge (ND-04) a satellite cone on the northern flank of the North Cone of Target A, recovering black, vesicular, sparsely olivine-microphyric basalt. The rugged topography of this volcanic complex required the filling of a few swath gaps in the shallower portions while proceeding south to dredge the summit of the South Cone. The dredge (ND-05) recovered a full load of variably altered to fresh scoria and blocks of sparsely olivine-clinopyroxene-phyric, black, vesicular basalt. A minor proportion of this load comprised highly oxidized equivalents. Once we could see the full bathymetry of the summit region we chose to offset northwest from the summit for a hydrocast (NH-02); In 400m depth, no plume was detected.

Day 3. Friday October 29th. We swath mapped back northeast again to the southern structures of Target B, choosing to dredge (ND-06) the summit of a morphologically young looking volcano (the northernmost of the pair of cones); Mn crusts and ashy sediments were retrieved indicating that this is a relatively old volcano.

The apparent collapse features shown on the Zellmer & Taylor bathymetric compilation associated with the structures west of Hunga Ha'apai appeared to be similar to those of major volcanoes such as "Volcano 1" in the southern Tofua Arc and Macauley in the Kermadecs; accordingly, these structures attracted our mapping attention. But after completing the swath map of this "Western Cone of the Target B complex", we did not observe any of the "sediment/debris flow waves" that were anticipated. Nevertheless, we dredged (ND-07) the summit region of "Target Area B West", recovering layered carbonate lithologies and some well-rounded pebbles of altered volcanic rock. On the swath map, a cone on the southern flanks of the major structure appeared very bright on the backscatter image; dredging the western flank of this cone (ND-08) recovered a full bag of poorly vesicular, sparsely olivine-microphyric basalt and a few rounded pebbles (probably exotic) of brownish-grey pumice. It is possible that some recent rejuvenation of this volcano has occurred.

The next target was the ephemeral island of Fonua Fo'ou (also called "Falcon") and apparent bathymetric highs to its south comprising the northern part of "Target B". We swath mapped around the southern and eastern flanks of the major structure of which the islands of Hunga Ha'apai and Hunga Tonga are remnants, and completed an anticlockwise circuit of the shallows reported on the chart indicating the former position of Fonua Fo'ou. Returning on a reciprocal course, the plan was to creep around on the shallower side of this first swath circuit. But after encountering depths of less than 20m during this tour, we desisted from any further mapping towards the core of the volcanic edifice, and dredged a number of cones encountered on its flanks.

The first of these dredge targets (ND-09) is one of a pair of domal structures on the western flank of Fonua Fo'ou; the recovery of corals, sponges, and algae-coated layered carbonates indicates these particular features are reefs. In contrast, dredges ND-10, ND-11, and ND-12 of cones on the northern flanks returned black, moderately vesicular, glassy and aphyric basalt.

Day 4. Saturday October 30th. In the early hours of Saturday, we commenced the swath run northwards to "Target C" and over the course of the next 7 hours, the mapping revealed a complex double caldera system with cones inside both calderas and numerous satellite cones on the caldera flanks. A hydrocast (NH-03) in the deepest part (1050m) of the northern caldera detected no hydrothermal plume activity but was sampled for shipboard pH and laboratory analysis of dissolved metals.

A dredge (ND-13) of a morphologically perfect cone on the southeast flanks of the southern caldera recovered a full bag of cobbles and boulders of sparsely microphyric quartz-feldspar-orthopyroxene-Fe-Ti oxide-bearing rhyolite, grading from dense black glass to white pumice in texture. The next dredge (ND-11) of a small cone on the southestern wall of the southern caldera returned a full bag of variably and slightly iron-stained, woody textured, and centrally inflated cobbles and boulders of feldspar-pyroxene-bearing dacite-rhyolite pumice. This lithology does not appear to be the same material as that of ND-13.

A hydrocast (NH-04) in the deepest part (830m) of the southern caldera revealed no evidence of a hydrothermal plume. Dredging (ND-15) of the largest cone within this southern caldera recovered weathered and iron-stained, dark grey aphyric pumice; this material appears to be older than that comprising the cones on the southeastern flanks of the southern caldera, and the variably (and stripey) grey-white vesicular dacite-rhyolite pumice dredged (ND-16) next from a large cone within the northern caldera. The final couple of dredges of Volcano C were executed on features on the northern flanks of the northern caldera: the first of these dredges (ND-17) was of a morphologically well-preserved cone, and retrieved a full bag of gradational vitrophyre-pumice, some of the latter with extreme vesicle elongation imparting a woody-texture. The second dredge (ND-18) targeted an area of strong backscatter that appeared to be a valley-filling lava flow, and recovered very fresh, black glassy dacite.

Day 5. Sunday October 31st. Moving northwards, we sailed a swath transit that took the ship over a small bathymetric high to the southwest of the subaerial volcano of Tofua. This feature proves to be a somewhat degraded caldera, and a dredge (ND-19) of a ridge extending from its northern rim recovered coral-encrusted blocks of volcaniclastic sandstone-siltstone in the chain bag, and black basaltic sand in the pipe dredges; the latter is presumably derived from Tofua. Continuing northeastwards, we then started swath mapping target Area D. By 5pm, a complex caldera structure with a prominent, relatively young-looking cone on the southern margin had been revealed. The first operation was a hydrocast in the northwestern corner of the caldera. During the cast, no transmission anomaly was detected. Dredging of a cone in this portion of the caldera (ND-20) recovered a full bag of angular blocks of massive black and grey lavas and beige-coloured pumice with no fresh glass.

A similar large load of diverse cobbles/boulders of variably altered white pumice to black andesite/dacite was recovered (ND-21) from acone on the eastern side of the caldera. In addition, a limited number of iron oxyhydroxide crusts formed a minor portion of the retrieval, but most of the load was smeared with this material. Grey mud with small clasts of similar lithologies to those in the main bag were trapped in the pipe dredges. A hydrocast (NH-06) in the throat of a crater-topped cone on the southern margin of the comples showed no transmission anomalies. A full bag of diverse lithologies was dredged (ND-22) from the western flank of the summit of this cone: moderately phyric (plagioclase-pyroxene), quite dense and welded in parts rhyolite/dacite; flow-banded pyroxene-plagioclase-phyric lava blocks; rounded cobbles of dense,plagioclase-phyric andesite; minor proportion of iron oxyhydroxide crusts.

Day 6. Monday November 1st. The final dredge (ND-23) at Target D aimed to sample an apparent (from acoustic backscatter) lava flow emitted from a small cone on the southern flanks of the caldera. A small load of black, angular blocks of dense, glassy, olivine-microphyric basalt was recovered.

During the transit around the subaerial (and near subaerial) volcanoes of Metis, Home Reef, and Late volcanoes northeastwards to Target F and the site of an eruption that

broke sea surface in 2001, we took another look at the transmissivity outputs from the first six hydrocasts. It became apparent that a number of plumes had in fact been detected: ~ -0.05% transmission anomaly centered at 500m and extending over a range from 450 to 600m in NH-01 (north flank of the north cone of *Volcano A*); ~ 0.02% centered (weakly) at 325m in NH-02 (south flank of the *same cone*); ~0.03% centred sharply at 300m and diffusively at 500m in NH-03 on the northern flank of the south cone of *Volcano A*; ~0.02% centered at 660m in NH-05 in the caldera of *Volcano D*. The range for transmissivity output readings for subsequent hydrocasts were accordingly reset as a result of these observations.

The first stages of swath mapping of Target F revealed a 7km-diameter caldera with numerous cones on the rims and flanks, and some lava flows draped down the walls into the floor of the caldera.

Day 7. Tuesday November 2nd. A transmission anomaly commencing at 520m and increasing to 0.1% towards the bottom (sampled at 5m off the EM300 bottom depth of 721m) was detected in hydrocast NH-07. With this real-time information, the niskins were sampled for the first time on this voyage for later helium isotopic analysis. Some hysteresis was observed in the new transmissometer, but the shapes of the down- and upcast signals were identical.

The first dredge (ND-24) at Volcano F targeted a small cone on the floor of and adjacent to the eastern wall of the caldera. A full load was recovered of fresh, black, plagioclase-bearing lava with well-formed, glassy crusts up to 2cm thick. The trace amounts of Fe-Si oxyhydroxide coatings on these blocks suggest relatively recent eruption. The second dredge (ND-25) sampled a morphologically young cone on the eastern inner caldera wall, achieving a small recovery of fresh, black, sparsely plagioclase-phyric lava, similar to ND-24 and possibly of the same age. The third in this initial series of dredges (ND-26) sampled the largest cone on the outer NE margin of the caldera. A 3/4 full load was retrieved of weakly weathered, pale to dark grey, variably vesicular aphyric lava probably dacitic in composition. The commonest lithological variety is pumiceous, some of it deeply weathered to clay.

The caldera of Volcano F is ellipsoidal with a long axis aligned NW-SE. We needed to swath more of the northwestern portion of the caldera, the next operation targeted the cone and crater complex on the northern margin of Volcano F caldera. A half-full dredge bag (ND-27) was recovered comprising angular clasts of black basaltic scoria; many of these clasts are highly centrally inflated with extremely fragile-looking whiskers of glass. Some of the recovered has a small amount of carbonate coating and looks older giving the impression of a bimodal age distribution for the dredge recovery.

The swath map had revealed a number of apparent flows, either lava or debris, draping the northern wall of the caldera. Dredge ND-28 of one of these flows recovered a 1/4 full bag of black, massive, glass-rinded basalt fragments indicating these are lavas. The next dredge (ND-29) of a cone on the floor of the central west portion of the caldera

retrieved similar material: 15 kg of fresh, glass-rinded, poorly vesicular basalt clasts. Similar material was also recovered from a prominent young cone complex in the northwestern wall of the caldera (ND-30). Morphologically similar-appearing cones and flows are developed on the outer western flank of the caldera. Dredging of one of these (ND-31) retrieved 20 kg of carbonate-coated, weathered, black, aphyric, variably vesicular to massive volcanic rock (possibly basalt). These flows are clearly older than those inside the caldera.

Day 8. Wednesday November 3rd. The final operation at Volcano F was a dredge (ND-32) on the south-trending scarp of the southern wall of the caldera. Fifteen kg of heavily carbonate-covered, weathered and altered, plagioclase-phyric, massive andesite was recovered.

Leaving Target F, we transited eastwards to a circular, nominally 99m-deep structure shown on the Admiralty chart at 18º 20'S, 174º 13.5'W. No such shallow structure exists at this location. Bypassing Toku and Fonualei, we swath mapped the shallow region (Target H) at 17º 56'S, 174º 15'W north of these islands where evidence of volcanic activity had been reported in 1964 and 1965 with reported depths of 139 and 161m. Our swath mapping did not reveal any possible shallow volcanic structures at this location but on the northern part of the Target H area, we discovered a new volcanic cone with a summit of 150m depth at 17º 51'S, 174º 12'W. However, a dredge of the western flank of the morphologically young-looking summit area recovered a 1/4 full bag of solely reefal carbonate indicating this volcano has not recently been active.

We had reached the latitude of the southern termination of the Fonualei Rifts - a nascent N-S-striking backarc basin to the west of the Tofua Arc. So at this point we transited westwards to begin the swath mapping of the southern portion of the Rifts. Our initial survey was set to cover the Rifts between 17º and 17º 35'S and continued through the rest of the day revealing in beautiful detail, deep (~3000m) sediment-covered floors, speckly lava-flows, faulted volcanic ridges and cones.

Day 9. Thursday November 4th. Swath mapping of the Rifts continued through the night until 2000 hours. A series of dredges was planned with the intention of spatial (with inherent potential temporal) and morphological coverage. The first dredge in this series (ND-34) targeted the apparent active crest in the centre of the northern end of this southern segment of the Fonualei Rifts, recovering 10 kg of very fresh, glass-rinded basalt flow chips and cobbles in the pipe dredge and nothing in the main bag. The next dredge (ND-34) aimed to sample a prominent cone in between two overlapping segments of NNE-SSW-striking, active ridges in this northern zone, but came up completely empty.

Day 10. Friday November 5th. Thinking that perhaps only glass chips were being generated by the dredging activity, and not being trapped by the relatively coarse chain mesh of the main bag, a net liner was installed, and a second attempt (ND-36) on the prominent cone made. Again nothing was recovered despite having 1845m of wire out

in about 1480m water depth, but no drop in tension with initial dredge-bottom contact was observed. Subsequent experience has showed that at least 2100m of wire would have to have been deployed to contact the bottom. For example, the next dredge (ND-37) successfully recovered a full bag of fresh black, sparsely phyric basalt with well-developed glass crusts from a small cone at the northern end of the eastern overlapper in this northern portion of the southern segment of the Rifts. With a target depth of 1650m at the first waypoint, 2205m of wire had to be deployed before bottom contact was seen, giving a [wire out on bottom]/[target depth] = 1.34. In subsequent dredges, this value has ranged from about 1.3 to 1.6.

At this point, we began a west to east transect across the Rifts at a latitude of about 17° 05'S. The first dredge (ND-38) towards the western end of this transect on a medium-sized discrete cone retrieved half a bag of weakly weathered large blocks of aphyric basalt, locally with poorly developed glass rinds. Moving eastwards, a young-looking (i.e., high acoustic backscatter) lava field was dredged (ND-39) returning a 1/3-full bag of black, aphyric, glass-rinded pillow fragments; some internal fracture surfaces of these fragments are stained yellow or bluish grey, perhaps indicating proximity to hydrothermal activity. A 3/4 full load of glass-rinded, black, sparsely phyric (olivine and plagioclase) basalt pillow fragments were recovered in the next dredge (ND-40) from the NW flank of the most prominent cone on the central ridge of this transect across the northern end of the southern segment of the Rifts. A full bag of glass-rinded flow tops of black, variably vesicular pillow basalt was then retrieved (ND-41) from the upper NW flank of the central ridge, and another full bag (ND-42) of slightly altered, glass-rinded, grey-black, variably vesicular olivine-phyric basalt from the central high of the eastern ridge. The final target (ND-43) in the transect was a medium-sized discrete cone with strong backscatter at the easternmost end of our swath coverage at this latitude. Angular boulders and cobbles of slightly weathered (thinned and degraded glass rinds) of moderately to highly vesicular, sparsely olivine-phyric basalt was recovered.

The immediate overall plan was now to move southwards, dredging and hydrocasting, prior to swathmapping the southern termination of the Fonualei Rifts, and then to return east to the Tofua Arc (Targets I and J) prior to returning to the next segment of the Rifts in their northward continuation.

Accordingly, the first step in the execution of this plan was a vertical hydrocast (VH-08) in 2445 m of water over the southwestern extension of the central ridge in this southern segment of the Rifts. Apart from a reconnaissance for locally-sourced hydrothermal plumes, a primary aim of this hydrocast was to establish the presence (or otherwise) of the ~1700m deep, regional ^{3}He plume associated with the northern end of the Lau Basin-Fiji-Samoa region. A 0.01% transmission anomaly centred at this depth was in fact detected, and the cast was sampled for ^{3}He analysis, pH and dissolved metals. A larger 0.02% anomaly was also detected, centred at about 1250m depth.

Day 11. Saturday November 6th. A dredge (ND-44) with the final waypoint equivalent to that of the VH-08 hydrocast retrieved a full load of black, aphyric basalt with well-developed 1cm-thick glass crusts. Some of this material is weakly weathered with orange-yellow staining along fractures. Continuing southwards, the next dredge (ND-45) targeted a cone on the central ridge of the southern segment of the Fonualei Rifts. A full load of black, slightly weathered surficially, glass-encrusted, aphyric basalt was recovered. The NW flank of the largest cone on the southern ridge was the next dredge location (ND-46); a bulging haul of black aphyric basalt pillow fragments, variably vesicular (especially in the cores of the pillows) with moderately well-developed glass rinds returned. Prior to leaving the summit region of this cone at 1050m depth, we deployed a hydrocast (NH-10). No transmission anomalies were observed.

Up to this point, we had not mapped the southern termination of the Fonualei Rifts. Over the next four hours, this task was completed and a final couple of dredge targets selected; the first of these (ND-47) was on a cone of the apparent southern propagator. A full bag of cobbles and boulders of black-grey glass-encrusted, variably vesicular pillow and flow fragments of aphyric basalt was recovered.

Day 12. Sunday November 7th. The final dredge in the southern segment (ND-48) on the southern rift flank of the largest cone retrieved a full bag of cobbles and boulders of glass-rinded, black-grey, variably vesicular pillow and flow rinds and interiors. A minor lithology consisted of grey-brown hydrothermally altered equivalents of the most abundant rock type.

The rest of Sunday was initially occupied with swath mapping of Target I back eastwards on the Tofua Arc. This proved to have a double edifice structure: relatively large (x km across), flat-topped (at ym) and elongated NW-SE in the south; a smaller (z km) flat-topped structure at (d m) in the north. The flat top and pock-marked surface of the southern structure looked suspiciously like a drowned karst; two grabs (NG-01, NG-02) recovered coral fragments confirming this supposition. A number of software and equipment difficulties accompanied by an accident to the Cook's foot in the middle of operations ensured a demanding technical environment for completion of the grabs.

Dredging of a cone on the southern flank of the northern structure (ND-49; ND-50) experienced comparatively strong tension pulls (up to 8 tons) retrieving disproportionately small amounts of reefal limestone, but confirming overall the volcanic quiescence for Target I.

The ship transited ENE over a zone of reported shallow water (finding nothing) and then NE to continue swath mapping through the night and next day of one of the largest submarine (supposedly volcanic) structures on the northern Tofua Arc: Target J.

Day 13. Monday November 8th. Target J proves to have southern and northern (larger) portions. Much of both these edifices are volcanically inactive and a planed-off platform, but a single caldera occurs on the southern margin of the southern platform. A hydrocast (VH-11) detected a very faint transmission anomaly at about 460m (caldera sill depth) on the downcast but nothing on the upcast. Two dredges (ND-51, ND-52) of "cones" within the caldera returned Fe-Mn-stained cobbles and boulders of volcaniclastic sediments, and some altered, old-looking lavas, casting doubt on the hypothesis that these are recent volcanic structures. The only obvious volcanic feature associated with the northern platform is a morphologically well-preserved small cone on the southwestern flanks. Nevertheless, this cone is also old given the Fe-Mn-stained, altered lavas retrieved by dredge ND-53.

Day 14. Tuesday November 9th. Satisfied that no evidence for recent volcanism would be forthcoming from Target J, we sailed northwards to K; yet another planed-off, degraded volcanic platform/caldera complex was revealed with a single cone in its northern portion. A dredge (ND-54) recovered large boulders of plagioclase-pyroxene-phyric andesite that are clearly not recent eruptive products. An attempt to sample the deeper portions of the northern spur of the innder caldera wall of Target K (ND-55) retrieved weathered, Fe-stained blocks of intermediateSiO_2 composition, Mn-coated deep-sea corals, and some live corals (*Enallopsammia rostrata*).

Satisfied with the coverage of this portion of the Tofua Island Arc, we transited westwards to study the next section of the Fonualei Rifts, sailing the first section from north to south and connecting with the coverage of the southern portion.

Day 15. Wednesday November 10th. Our first target of the day was to repeat the dredge (ND-35) which failed to find bottom on the cone in the central northern portion of the southern segment of the Fonualei Rifts. Due to some misunderstandings, the dredge (ND-56) was conducted in the wrong direction, only clipping the summit of the cone, and retrieving some iron oxyhydroxide crusts, fresh black basaltic glass chips and some weathered pumice. The fourth attempt at this site (ND-57) finally did the trick with a full bag of fresh, black, glass-encrusted basalt. American colleagues had communicated the results of a MAPR campaign in the Fonualei Rifts conducted during October 2004; these data were used to deploy a hydrocast (NH-13) at a site on the northeastern portion of the Rifts.Faint plumes were detected at 1400m, 850m, and 750m.

We moved northwestwards, guessing that the magmatic axis is currently active in this direction. A dredge (ND-58) on the northwest flank of the ridge crest recovered a full bag of very fresh, glass-encrusted, ropey (and breadcrusty) exteriors and vesicular interiors, of basalt pillow fragments. Similar material was retrieved from the next dredge (ND-59) of the northern termination of this ridge crest segment.

In order to examine the regional characteristics of the water column, we conducted a hydrocast (NH-14) in the deepest (2085m, and enclosed) basin in between rift segments in this central northern portion of the Rifts. A very faint transmission anomaly centred at 1250m was observed.

Knowing where the active magmatism is occurring in the Fonualei Rifts, and given the available bathymetry of the southern arm extending from the Mangatolu Triple Junction (15º 36.74'S, 174º 49.36'W), we now began to explore for the active magmatic zone linking the two. Initial swath mapping followed by dredging of this region commenced.

Day 16. Thursday November 11th. The first dredges (ND-60, ND-61) of this zone returned 1/2 full and full bags respectively of black, very glassy, basaltic pillow rinds and vesicular interiors. Sampling of the western summit of the largest cone in a pull-apart basin in the central northern portion of the Rifts revealed (ND-62) moderately fresh basalt pillows with partly degraded glassy crusts. Fresh black aphyric basalt pillows with exceptionally well developed glass crusts (up to 3cm thick) were recovered (ND-63) from the inner flank of the NW wall of pull-apart basin.

A hydrocast (NH-15) in another deep basin (2535m) between ridge segments did not detect any obvious transmission anomalies.

Further swath mapping to the northwest established the morphology of the transition between the South Mangatolu ridge and the Fonualei Rifts: no single axis and a complex series of shear-affect ridges and basins.

Day 17. Friday November 12th. While the ship reset its clocks to Samoan local time, we decided to continue with Tongan Time in the Operations Room rather than experiencing a "Groundhog Day" effect. Continuing the dredging of the zone between South Mangatolu Ridge and Fonualei Rifts, fresh to slightly weathered, black glass-encrusted aphyric basaltic pillows were recovered during a series of dredges (ND-64, ND-65, ND-66) in this zone.

A hydrocast (NH-16) on the ridge crest of the northern end of a ridge segment in the central Fonualei Rifts detected faint transmission anomalies at 750m and 1600m.

We began a final dredging and hydrocasting sweep across the central Fonualei Rifts prior to exploring the South Mangatolu Ridge. A dredge (ND-67) from the northern end of a ridge segment on the SW flank of the central Fonualei Rifts retrieved two lithologies: grey, highly stretched ("woody-textured") grey pumice and slightly degraded, black glass-encrusted and variably vesicular basalt pillow fragments.

A hydrocast (NH-17) on a cone on the eastern flank of the Fonualei Rifts detected a moderate transmission anomaly at 1250m. Dredging of the eastern flank of this cone (ND-68) recovered fresh, black, glass-encrusted basaltic pillow lava fragments up to ~ 45cm across.

Day 18. Saturday November 13th. Heading northwards, we swath mapped our way up the South Mangatolu Ridge to the Mangatolu Triple Junction[1] – a spectacular ridge-ridge-ridge morphological feature. A hydrocast (NH-18) at the centre of the Triple Junction encountered faint transmission anomalies at 1200 and 1400m, and then barely above background all the way from 2000m to the bottom at 2250m. Dredging (ND-69) of one of four conical structures at the Triple Junction recovered fresh, black, aphyric, poorly vesicular pillow basalt.

Working our way back southwards, we hydrocast (NH-19) on the crest of the South Mangatolu Ridge, encountering a diffuse and faint transmission anomaly centred at 2300m. Dredging (ND-70) of this location retrieved fresh, black, glass-encrusted, poorly vesicular basalt pillow sections up to 50cm across.

It was time to return to the axis of the Tofua Arc and the remaining targets (L, M, N, etc). A swath traverse covering the northern and eastern limits of the Fonualei Rifts prior to an easterly transit to Target L commenced at ~ 2100 hours.

Day 19. Sunday November 14th. Through to midday, we swathmapped target L, identifying a relatively degraded structure, with a young adventive cone on the southwestern flank. A dredge (ND-71) of this cone recovered glass-encrusted, slightly weathered black basalt with small phenocrysts of plagioclase and olivine. This is evidence however, that the arc at the latitude of target L is rejuvenated.

Moving northwards, we searched the western flank of the island of Tafahi for any evidence of additional volcanic edifices to the west. Problems with the multibeam navigation had been developing during the day, and at this moment, the EM300 software froze. After a couple of hours of intense work, the system was restarted and the swathmapping resumed. No evidence in fact was found for any additional calderas or cones, so we continued northwards cautiously in the vicinity of numerous mapped shoals of Curocoa (Target N).

Day 20. Monday November 15th. An uncharted but substantial cone shoaling to less than 30m depth on the western edge of the mapped shoals was targeted for the next dredge (ND-72); a full load of dacitic blocks varying from massive, dense and grey-black to beige pumice was recovered from a satellite cone on the flanks of this edifice. Given the difficulty of working in waters less than 50m deep (in darkness), we decided to transit to the northwest towards Target O. This is a spectacular 15-km diameter caldera with a central cone. American colleagues had reported strong intracaldera hydrothermal plumes at about 1200m depth, consistent with a source near the summit of this cone. A remarkable haul of black, vesicular basalt with glassy rinds was recovered by dredging

[1] Note that Mangatolu is Tongan for triple junction, so it is in fact tautologous to write "*Mangatolu Triple Junction*".

the northwest flank of the cone (ND-73). Included in the recovery was a substantial proportion of hydrothermally altered equivalents of this major lithology, including some sulfide-rich material and small spheroids of native sulfur. The cone is clearly host to a major hydrothermal system.

The final dredge (ND-74) of *NoToVE* was on the crest of a spreading ridge, part of the Northeast Lau Spreading Centre, located immediately northwest of the caldera of O. Recovery comprised slightly degraded, glass-encrusted , spectacularly olivine-clinopyroxene-phyric, variably vesicular pillow rims and interiors together with some exotic blue grey pumice.

At 17.30 hours, the transit to Apia commenced for docking at 09.00 hours on Tuesday November 16th (Tongan time) or Monday 15th local time.

Summary

Overall, *NoToVE* was an outstanding success scientifically. The 30 kHz swathmapper has revolutionised the way in which the study of seafloor volcanic and hydrothermal systems can be conducted. While 12kHz surveys serve as a most useful guide to regional seafloor bathymetry, and we were fortunate in having access to a recent 12 kHz swath of the southern Fonualei Rifts, the *NoToVE* voyage demonstrates the distinct advantage of high frequency swathmaps for detailed geological work.

We have within a period of 3 weeks defined the extent and detailed morphology of numerous submarine volcanoes in the northern Tofua Island Arc. The first high resolution bathymetric maps of some of the youngest backarc basins in the world have been generated, and the extent of the constructional magmatism occurring in these basins has been defined together with associated structural deformation patterns. In addition to extensive sampling of the magmas forming the arc edifices and the floors of the Fonualei Rifts and South Mangatolu spreading system, we have established the cessation of arc magmatism adjacent to the newly forming Fonualei Rifts, and gained insight into the initial tectonic stages of formation of arc volcanoes and backarc basins.

The RV *Southern Surveyor* is fundamentally well equipped for this particular kind of research. While the transmissometer performed well on this voyage, experience has now shown that a nephelometer appears to be more sensitive in the hunt for hydrothermal plumes on future National Facility voyages.

Personnel

Professor Richard J. Arculus – ANU-Earth & Marine Sciences, petrology/tectonics
Dr Tim Worthington – Christian-Albrechts-Universität zu Kiel, petrology/tectonics
Mr Chris Dale – Univ. of Durham (UK), petrology-isotopes
Ms Sam Burgess – ANU - RSES, zoology
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Mr. Kurt Worden – GA, petrology/tectonics
Ms Nicole Keller – ANU-RSES, petrology/volatiles
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Ms Niccole Mikkelson – ANU-Earth & Marine Sciences, petrology
Cameron Buchanan – A (Canberra), swath mapping
Bob Beattie – (Voyage Manager)CSIRO (Hobart), Computing Support
Jeff Cordell – CSIRO (Hobart), Electronics Support
Rennie Vaimo'unga – Tonga Observer

Crew members and their position on the ship:
Ian Taylor – Master
Rob MacManamon – First mate
Samantha Duriane – Second Mate
Roger Thomas – Chief Engineer
Robert Cave – First Engineer
Seamus Elder – Second Engineer
Malcolm McDougall – Bosun
Russell Williams – Integrated Rating
Fiona Perry – Integrated Rating
Keith Mitchell – Integrated Rating
Tony Hearne – Greaser
James McGarvey – Chief Steward
Gerald Hogg – Chief Cook
Robert Cumming – 2nd Cook

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On board, the support of and enthusiasm for the Voyage objectives displayed by Bob Beattie (Voyage Manager) coupled with his invaluable computing support is much appreciated. Jeff Cordell (electronics) was outstanding in his general problem solving and specific support of the hydrocasting effort. For the second time this year, the enthusiastic support of our swath mapping goals and the remarkable expertise displayed in the achievement of these goals by Cameron Buchanan (GA) was inspirational and contributed hugely to the overall scientific success of *NoToVE*. The safe and efficient conduct of operations by the RV Southern Surveyor's crew was exemplary, and the vital nutritional support during these efforts much appreciated. Finally, the Government and people of the Kingdom of Tonga are thanked for their permission to conduct this research in their territorial waters.

Richard J. Arculus
Chief Scientist