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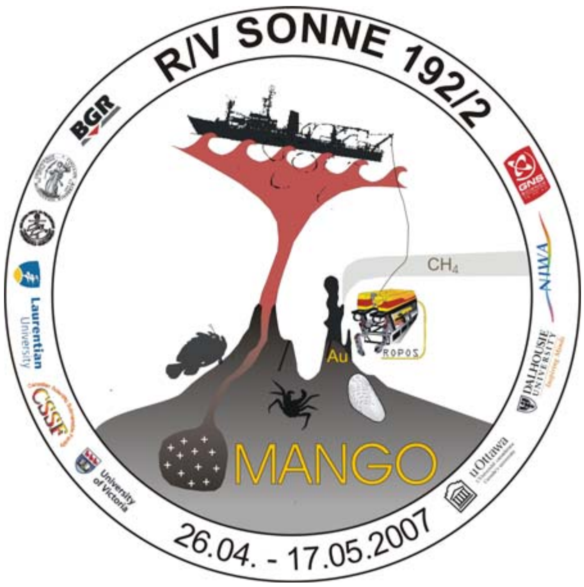
Cruise Report SONNE 192/2

MANGO

Marine Geoscientific Research on Input and Output
in the Tonga-Kermadec Subduction Zone

Marine Geowissenschaftliche Untersuchungen zum In- und Output
der Tonga-Kermadec Subduktionszone



Auckland, New Zealand – Suva, Fiji
26 April – 17 May 2007

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1. SUMMARY

The cruise SO-192/2 MANGO of R/V SONNE was a joint German-Canadian-New Zealand expedition to explore the Tonga-Kermadec arc, a 2500 km-long chain of active submarine volcanoes in the western Pacific, using the Canadian remotely operated vehicle ROPOS. This expedition continued a long-standing cooperation program on the study of submarine volcanic and hydrothermal systems in the western Pacific, including three previous expeditions to this region. SO-192/2 aimed at the investigation of submarine volcanoes and calderas studied and identified by our group in 1998, 2002, and 2005. The Tonga-Kermadec arc is the single largest continuous chain of submarine arc volcanoes in the Pacific Ring of Fire and one of the most volcanically active. The cruise aimed at the understanding of the significance of this volcanic chain in terms of its impact on ocean chemistry, biological productivity, marine resources, and hazards.

Cruise SO-192/2 visited volcanic complexes and associated vent sites at the southern and northernmost Kermadec and the southern Tonga volcanic arcs, and at the southern Valu Fa Ridge (Figs. 1.1, 1.2). Key objectives of this program were to study the fluid and geochemical input and output in the Tonga-Kermadec subduction zone in order to examine the relationship between tectonic, magmatic and hydrothermal processes along this volcanic chain. The project aims at the characterization of the subduction dynamics and to establish the relationship between the magma genesis, the volcanic and eruption processes, and the fluid dynamics with the discharge of hydrothermal fluids at caldera systems and eruption craters on the shallow ocean floor.

A total of 84 stations were completed including 16 ROPOS stations, 36 TV-grab stations, 9 CTD stations and 5 wax corer stations. A total of 18 SIMRAD EM 120 lines were completed representing 2215 nautical miles or 252 hours of swath bathymetry mapping. Sea conditions were generally good with only two days of limited operational capability. There were no problems with either the ship or shipboard equipment.

Hydrothermal activity was known to exist along the Tonga-Kermadec island arc system from several international research cruises including SO-135 and SO-167, and the 2005 SITKAP cruise. Hydrothermal activity was initially studied during SO-135 at the Calypso vent sites, offshore Taupo volcanic zone and the Clark and Brothers Seamount along the Kermadec island arc. The extensive mapping and dredge program during SO-167 encountered for the first time hydrothermally altered basalts, basaltic andesites and pumiceous rhyolites at four volcanoes along a 650 km segment of the Tonga island arc. A follow-up survey during the 2005 SITKAP cruise using the PISCES submersibles from the Hawaiian Undersea Research Lab (HURL) discovered extensive hydrothermal activity and high-temperature vents associated with prominent caldera systems at Volcanoes 1 and 19. The vents showed strong evidence for phase separation processes and related base and precious metal precipitation. Initial sampling program focused on the characterization of the discharging fluids and associated precipitates. First spectacular results and limited sampling capacities and time during the use of the PISCES submersibles made it necessary to revisit the sites during SO-192/2.

The cruise SO-192/2 was highly successful. The first ROPOS dive (R1039) proved the successful installation on board R/V SONNE and was deployed at the Calypso Vent Fields. Low-temperature vents were encountered at the southeast and northeast margin of a northeast-trending linear fault zone surrounded by uplifted slabs of hydrothermally indurated ash. Venting in the 190 m deep Calypso fields shows evidences of phase separation processes at depth. The seafloor is characterized by areas of bacterial mat, bubble streams and shimmering water, slabs of sulphur-cemented ash rich in hydrocarbons and massive anhydrite. Fluid sampling indicated a mixture between seawater and hydrothermal fluids represented by weak acidity and very high H_2S contents. A diverse sessile macrofauna, fishes and invertebrates

(anemones, sponges, polychaetes, crustacean, mussels) are concentrated around the vents. The characteristic Bathymodiolus spp. was identified from this vent field for the first time.

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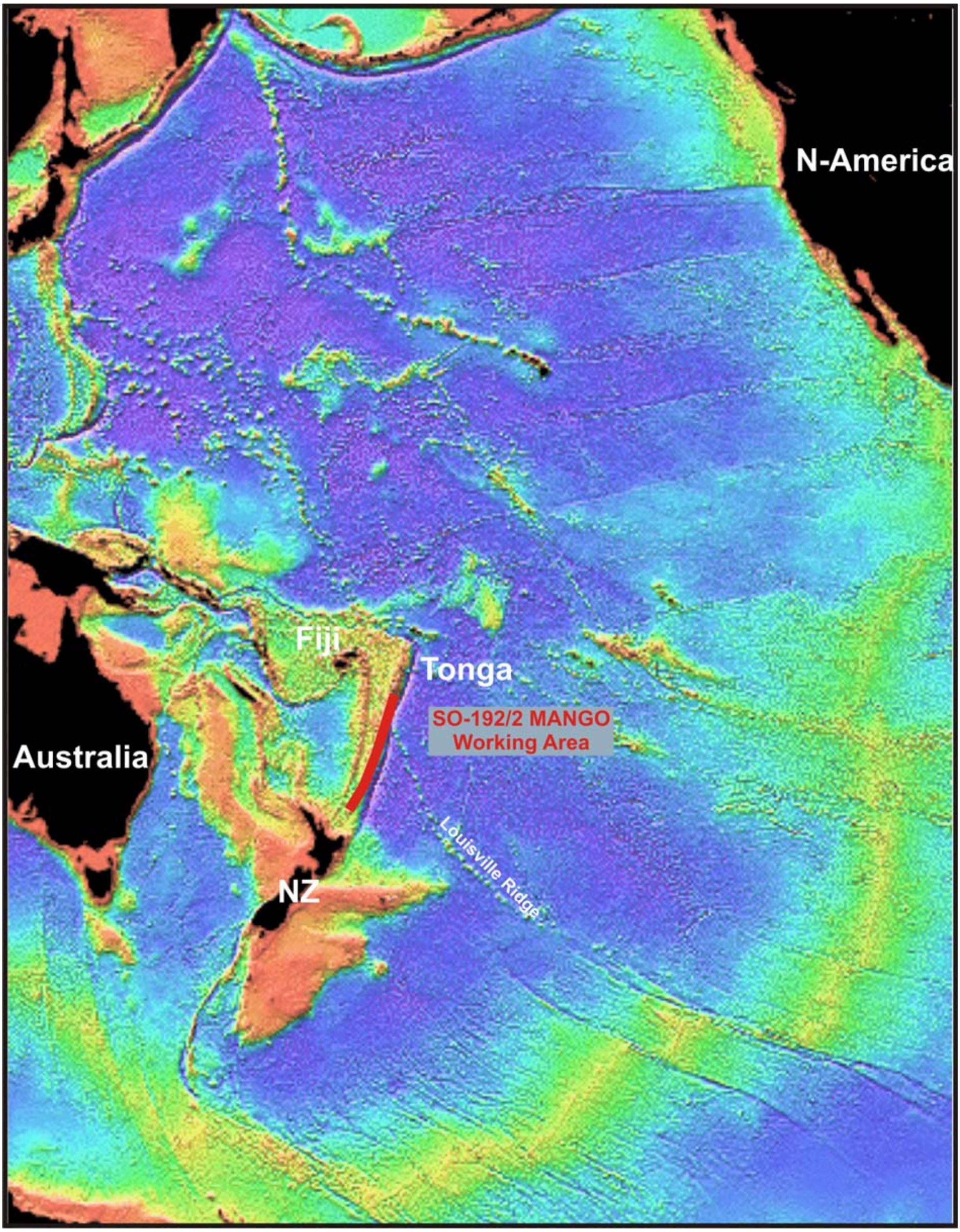


Fig. 1.1: Overview of the SO-192/2 work area along the Tonga-Kermadec Island arc, SW Pacific.

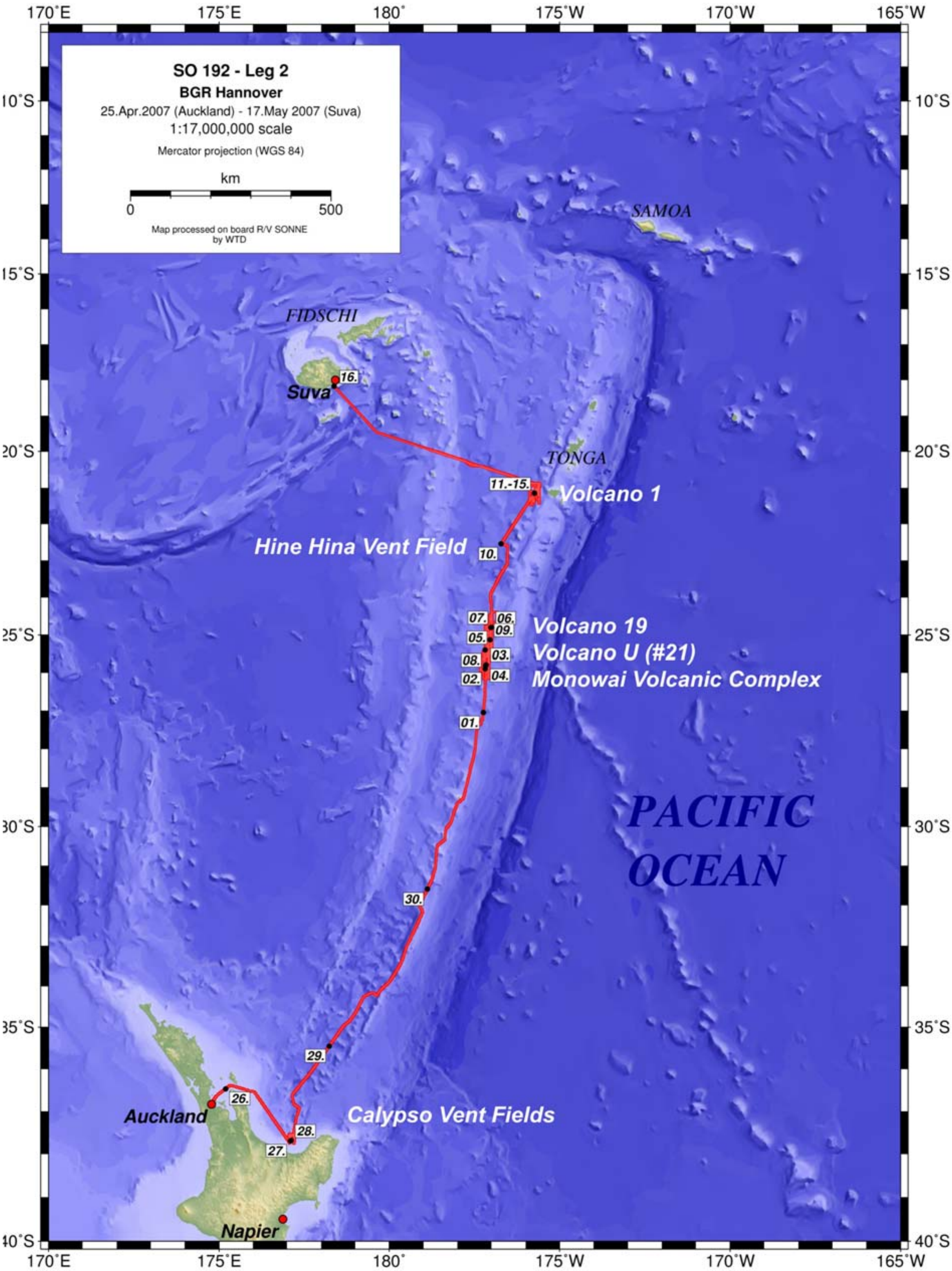


Fig. 1.2: Work stations and course of the SO-192/2 cruise. The cruise started in Auckland, New Zealand and ended in Suva, Fiji.

Diving at the active summit of the Monowai Volcanic Complex (MVC) was affected by frequent steam explosions from a small cone building on the southern flank of the active summit. Audible "bumping" of the ship and visible discoloration and upwelling at the surface was noted in several places. Map comparisons between 1998 and 2004 inferred a collapse feature on the SE side of the volcano and a change in summit depth (Wright et al., 2007). The new map from the SO-192/2 cruise shows that near summit eruptions over the past three years have completely infilled the collapse scar and buried the reconstructed summit cone. The recent summit at 98 mbsl has arisen ~40 m since this last mapping. The Monowai Volcanic Complex (MVC) is built on a larger, low-relief basaltic-andesitic lava shield. The base of the original constructional edifice is exposed in the deepest part of the eastern caldera wall. It exposes a stepped slope of massive pillowed basalt, slopes covered by blocky talus, coherent flow material and bedded volcaniclastic material, covered by fresh scoria and black sand. The mapping program focused on the study of the regional structural setting. The MVC is located within a pronounced (approx 30 km wide) northeast-trending rift that is a product of NW-SE extension. This extension has affected the arc at regular intervals and the northeast-trending structural pattern pervades in the fore-arc volcanoes along the entire Tonga-Kermadec Arc. Low-temperature vents were identified at “Mussel Ridge”, a linear outcrop of massive coherent basalt, heavily encrusted by mussels. Numerous areas of low-temperature venting were located at a depth of about 1150 m and dense coverage of mussels was mapped on the flank and along the northwest trending summit of “Mussel Ridge”. The sampled material from the vent sites comprises barite-pyrite and sulphur-rich crusts and altered micro-vesicular basaltic lava. ROPOS and TV-grabs recovered a diverse macrofauna with more than 900 organisms. Key findings included the vent mussel Bathymodiolus sp. and the tube worm Lamellibrachia spp.

The summit crater of the arc volcano (“U”, #21) immediately north of Monowai is devoid of hydrothermal activity and macrofauna. Geological observation revealed a swarm of dikes up to 300 m thick with weakly bedded coarse volcaniclastic material at the very base. The dikes die out toward the top of the caldera wall and the uppermost part of the wall consists of unconsolidated ash and lapilli. Sampling recovered plagioclase-pyroxene phyric and slightly vesicular basaltic lava.

Diving at Volcano 19 aimed at the detailed sampling of volcanic rocks, sulphate-sulphide chimneys and hydrothermal crusts, fluids and vent fauna from the two spatially distinct active fields of hydrothermal venting that were identified during the SITKAP cruise. The survey of the field associated with the western caldera structure at Volcano 19 relocated an extensive field of numerous Fe-oxide chimneys and low-temperature vents up to 39°C along the base of the southern wall. The area between the 2 to 3 m high chimneys is covered with Fe-oxyhydroxide crusts. These edifices are concentrated near outcrops of basaltic dikes. The chimneys are always densely covered by microbial mats. Shimmering water is venting from cracks within hydrothermal barite crusts and indurated volcanic ash. A 112 °C vent in the centre of the chimney field that was measured in 2005 during SITKAP was sampled for water, gas, hydrothermal precipitates, bacterially precipitated Fe-oxides, and vent fauna. A second field occurs some 500 m further to the east and greatly extends the area of hydrothermal venting in this part of the caldera. The high-temperature vents are associated with the summit cone complex of Volcano 19 at water depths between 385 and 540 mbsl. An area of approximately 800 x 800 m comprises clusters of large barite and anhydrite chimneys up to 15 m high, and is covered by extensive deposits of Fe-oxyhydroxides and hydrothermally cemented ash. The western flank of the cone complex shows fields of Fe-oxyhydroxide chimneys similar to those within the caldera. The sulphate-sulphide chimneys are characterized by vigorous venting of clear fluids with temperatures on the seawater boiling curve, pH of 4.6-6.1, and low gas contents. The occurrence of phase separation is evident and can be seen as flame-like jets of steam (H_2O vapour) discharging from multiple chimney orifices. The highest temperature vent near the centre of the summit cone site is two-phase and has discharge temperatures of 270°C. Pyrite, sphalerite-wurtzite, galena and chalcopyrite line the interiors of the chimneys whereas the outer rims are enriched in As sulphides. The biggest edifice ("Big Fella") on the summit cone complex has a height of ~15 m and carries a prominent beehive structure on its top (385 mbsl). The highest vent temperatures measured were 247°C. The fluid sampling program retrieved 6 fluid and 9 gas samples at vent temperatures between 32 und 270 °C. Rock sampling recovered a variety of glassy basaltic volcanic bombs, vesicular phyric lava, glassy aphyric lava, and volcanic ash. Bathymetric mapping during night times confirmed the continuous NW-SE extensional pattern and northeast-trending volcanic and tectonic structures which extend well across the transition zone between the Kermadec and the Tonga arcs. This structural pattern is obviously not affected by the subduction of the Louisville volcanic ridge at 25°S. A diverse vent fauna of crabs, shrimps, polychaete and vent worms, mussels, and sea stars populate the summit field. A total of 268 organisms were sampled, including the rare flat fish Symphurus spp. which was located among sulphur-cemented ash at the southern edge of this field. A new clam field was found in the depression on the southwest flank of the summit complex.

The work at Volcano 19 could not be finished due to an approaching pressure low. It was decided to revisit the Hine Hina vent field at the southern Valu Fa ridge, Lau basin. The Hine Hina field was last visited in 1991 by the French submersible Nautile and photographed during an OFOS survey in 1998 during SO-167. The Hine HIna site approaches the arc front (volcano 8) to within 25 km. A ROPOS dive and subsequent sampling aimed at the comparison of venting characteristics and faunal similarities and dissimilarities between arc and back-arc shallow seawater hydrothermal systems. The transit was used for an ambitious mapping program in the area between the Tonga island arc and the Lau basin. Bathymetric mapping supplemented the lines from the SO-167 campaign. ROPOS dive R1049 was deployed at the SO-167 OFOS track and located the French marker #98 in a field of mussels on a flank of a pillow cone adjacent to the main ridge segment. The recent hydrothermal activity is low temperature and diffusive, and outlined by patches of alive vent fauna (Bathymodiolus vent mussels, limpets, squat lobsters). Low temperature discharge causes the widespread formation of weakly consolidated iron- and manganese-hydroxide crusts. Pyrite and barite encrusted pinnacles of ash were located. One area of relict chimneys was found at the southeast end of the ridge segment in an area where Nautile had recovered stockwork mineralization. Massive blocks of Cu-rich sulphides from relict chimneys were sampled by ROPOS and by a subsequent TV-grab station at this site. Fauna comprised two species of Bathymodiolus vent mussels, a large limpet species, and squat lobsters. Good sampling success and improving weather conditions allowed the return to the original program.

At Volcano 1, low- to medium-temperature venting was found in 2005 to be associated with two pits of a post-caldera chain of craters and on the adjacent flanks of the SW post-caldera scoria cone. Venting at a maximum temperature of 70° C was found at two locations, however the volume of gas and the temperature of the vents noted during the PISCES dives had decreased since 2005. A survey of the western end of the central pit crater found a large area of Fe-oxide encrusted ash (>60 m diameter) with abundant bacterial floc, which was sampled for studies of Fe-oxidizing bacteria. A survey up the flank of the scoria cone south of the mussel field found patches of white bacterial mat and isolated patches of mussels on cemented ash blocks near the summit (100 m depth). Sampling recovered massive native sulphur crusts and numerous samples of strongly altered volcaniclastic rocks with crusts of very fine-grained pyrite and native sulphur in vesicles and interbedded with ash layers. Crusts of massive pyrite and marcasite with sulphur were sampled from the center of the mussel field (near marker #43). Fluid sampling occurred above the main mussel beds and sulphur-rich vents. The shallow water depths at the top areas of Volcano 1 result in the superposition of chemosynthetic and photosynthetic assemblages. An area of abundant flatfish was surveyed on the north flank of the scoria cone adjacent to the chain of craters. The flatfish Symphurus spp is very rare and discovered in this Pacific region for the first time. A detailed survey of the vent fauna was carried out in the mussel beds that occur on areas of sulphur-cemented ash along with plankton tows and water-column filtering. Recovered fauna included high concentrations of bathymodiolid vent mussels along with small crabs and gastropods, and Symphurus spp. The constructional features of Volcano 1 were studied during several caldera wall sections. Deepest exposures are characterized by massive coherent basalt und pillowed units represented by a dike or sill complex and lava flows. This grades into a steeply dipping dike complex about 150 m thick and into a block-rich to fine bedded volcaniclastic sequence that is capped by a thin section of finely bedded tuff. The entire section of block-rich volcaniclastic material is cut by numerous dikes subparallel to the caldera wall. Sampling collected a decent stratigraphic suite of the caldera wall. Scoria cones consist of blocky to coarse volcaniclastics intruded by numerous dikes. The upper part is covered by unconsolidated scoria, cinders, and local bombs. Large blocks covered by bacteria were observed at the summit, near 100 m depth possibly representing the remnants of a dome top. Sampling recovered basaltic vesicular, aphyric and partly glassy lavas. A linear ridge adjacent to the two scoria cones on the south side of the caldera may represent a series of overlapping cinder cones developed along the length of an eruptive fissure. Fresh volcanic bombs were recovered from this site and two successions of scoriaceous material were observed. There is no evidence of recent hydrothermal activity or degassing. The mapping program aimed at the supplement of the northern and western extension of Volcano 1.

2. ACKNOWLEDGEMENTS

We thank Captain Lutz Mallon, his officers and the crew onboard FS SONNE for their very high efficiency and excellent professional performance, help and advice. Although only the third time on board R/V SONNE, the set up, handling and daily operations of ROPOS worked without any significant problem. This is also true for the TV-grab, CTD and wax corer operations and for the extensive SIMRAD mapping programs during the nights. Sea and weather conditions, with few exceptions, were generally good throughout the cruise. Nevertheless, maintaining shipboard harmony, safety standards, enthusiasm and high efficiency throughout the 3 weeks cruise is not an easy undertaking. At all times potential difficulties were resolved calmly and professionally by the Captain, officers and crew. Thanks are also due to the shipping agents in Suva (Greg von Litzheim; Pacific Agencies Ltd.) and Auckland (Miles Cardis, McKayShipping) for their assistance with our logistic and travel arrangements. We particularly appreciated the efforts and co-operation of Rennie Vaiomo’unga (Ministry of Lands, Survey and Natural Resources, Nuku'alofa, Kingdom of Tonga), the New Zealand agencies and Wolfgang Mahrle (German Ministry of Foreign Affairs). We thank the Kingdom of Tonga for permission to work within their territorial waters along the south Tonga arc and Valu Fa Ridge. We also thank the New Zealand Government for permission to work within their territorial waters in the Bay of Plenty.

The MANGO (SO-192/2) project is funded by a Bundesministerium für Bildung und Forschung (BMBF) project award to Dr. Jan Scholten and Dr. Reiner Botz (University of Kiel), and Dr. Ulrich Schwarz-Schampera (BGR) (03G0192).

3. PARTICIPANTS

MANGO is a multidisciplinary international project led by the University of Kiel (Institute of Geosciences) and the Federal Institute for Geosciences and Natural Resources (BGR). Other participating research groups are the Ottawa University (Canada), the Laurentian University (Canada), the University of Victoria (Canada), Dalhousie University (Canada), the University of Aarhus (Denmark), NOAA Pacific Marine Environmental Laboratory (PMEL, USA), the National Institute of Water and Atmospheric Research (NIWA, New Zealand)), the Institute of Geology and Nuclear Sciences (GNS, New Zealand), the Ministry of Lands, Survey and Natural Resources (Kingdom of Tonga), and the Canadian Scientific Submersible Facility (CSSF). The 17 scientists in the Shipboard Scientific Party have diverse interests spanning the fields of hydrothermal systems, petrology, mineralogy, geochemistry, biology and tectonics. Full contact details for the shipboard scientists are listed in Appendix 1.

Shipboard Scientific Party:

Schwarz-Schampera, Dr. Ulrich	Chief Scientist	BGR Ore Deposit Research
Botz, Dr. Reiner	PI	IfG-Kiel Geochemistry
Hirdes, Dr. Wolfgang		BGR Ore Deposit Research
Ostertag-Henning, Dr. Christian		BGR Organic Geochemistry
Rutkowski, Julia		BGR Ore Deposit Research
Schmidt, Dr. Mark		Kiel University, Geochemistry
Rauch, Dr. Markus		Kiel University, Geochemistry
Westernstroer, Ulrike		Kiel University, Geochemistry
Haase, Dr. Karsten		University of Aarhus, Petrology
Hannington, Prof. Mark		Ottawa University, Economic Geology
Hocking, Mike		Ottawa University, Economic Geology
Langley, Sean		Ottawa University, Mikrobiology
Gibson, Harold		Laurentian University, Volcanology
Juniper, Prof. Kim		University of Victoria, Vent Biology
Stevens, Dr. Catherine		University of Victoria, Vent Biology
Metaxas, Prof. Anna		Dalhousie University, Vent Biology
Tracey, Dr. Di		NIWA, Marine Habitats
Leybourne, Dr. Matt		GNS, Hydrothermal Systems
Evans, Leigh		PMEL, Gas Geochemistry
Shepherd, Keith		CSSF ROPOS
Tamburri, Keith		CSSF ROPOS
Adamson, Roger		CSSF ROPOS
Mills, Reuben		CSSF ROPOS
Anger, Vincent		CSSF ROPOS
Cormany, Dan		CSSF ROPOS

Ship's Officers and Crew:

Mallon, Lutz	Captain		
Aden, Nils-Arne	1st Officer	Lindhorst, Norman	Chief Engin.
Büchele, Ulrich	2nd Officer	Diecks, Haye	2nd Officer
Klindler, Klaus	2nd Engineer	Buß, Jörg	2nd Engineer
Leppin, Jörg	Chief Electr.	Rieper, Uwe	Electrician
Großmann, Matthias	Systems Manager	Ehmer, Andreas	Systems Manager
Schlenker, Wilhelm	Doctor	Blohm, Volker	Fitter
Tiedemann, Frank	Chief Cook	Wieden, Wilhelm	2nd Cook
Schrapel, Andreas	Boatsman	Noak, Robert	Motorman
Kraft, Jürgen	Matrose	Drumm, Christian	Matrose
Lengen, Christian	Matrose	Marcinkowski, Przemyslaw	Matrose
Etzdorf, Detlef	Matrose	Wilde, Enrico	Matrose
Slotta, Werner	1st Stewart	Rudnicki, Gabriel	2nd Stewart
Stegmann, Tim	Apprentice	Heinrich, Finn Janning	Apprentice
Finck, Christian	Apprentice		

4. CRUISE NARRATIVE

The Shipboard Scientific Party boarded the R/V SONNE in Auckland in the afternoon on 25 April. The ROPOS submersible, its containers and winch as well as the other lab equipment had already been taken aboard on 24 April. ROPOS, sampling tools and lab equipment were unpacked during the afternoon. Winch and ROPOS were installed successfully and had a first test by the dock. R/V SONNE moved to the bunker station in the late afternoon on 25 April. An introductory and sampling field trip to the active volcano White Island offshore Taupo volcanic zone was organized for a small group of interested scientists on 25 April. During a helicopter flight out of the town of Whakatane, several plumes of shallow hydrothermal vents were observed in the water column and gave a first impression for the upcoming work in this area. A series of andesites, altered by intense fumarole activity, and few fluid samples were collected for comparison purposes. A first introductory meeting of the entire Shipboard Scientific Party was held in the ship's mess in the evening. R/V SONNE left its berth in Auckland at 09:00 on 26 April. Sea conditions were perfect, with a gentle swell and bright blue skies.

The first working area in the Bay of Plenty SW of the White Island volcano was reached in the evening of April 26th. The SIMRAD CTD-probe was deployed to calibrate the SIMRAD system, followed by the start of the mapping program in order to extend the bathymetry to the north and northeast (128 nautical miles). The first ROPOS dive (R1039) took place in the morning of the following day and focused on the Southern Calypso Vent Field. Low-temperature vents (V1-3) were encountered at the southeast margin of a collapse feature surrounded by uplifted slabs of sulphur-cemented ash marking the associated northeast-trending linear depression. Another cluster of vents (V4-8) was located in and around two 150-m diameter depressions marking the northeast end of the linear fault zone. Two more vents (V9-10) with the same northeast-trending orientation were discovered in the Northern Calypso Vent Field during the second ROPOS dive (R1040). Venting in the Calypso field is characterized by small areas of bacterial mat, bubble streams and shimmering water, and broken slabs of porous sulphur-cemented ash with notably red As-sulphide (realgar) and rich in hydrocarbons. TV-grabs recovered sulphur-cemented and silicified ash and massive anhydrite at water depths of 190 m. Fluid sampling occurred on two active vents (V4). First analyses indicated a mixture between seawater and hydrothermal fluids represented by weak acidity and very high H_2S contents. The biological program focused on the biodiversity, the ecology and food web studies in the surroundings of all visited vents. Sessile macrofauna, fishes and invertebrates (anemones, sponges, polychaetes, crustacean, mussels) are concentrated around the vents. A total of 216 organisms were sampled from vent No. 4 by ROPOS and TV-grab. For the first time, the characteristic Bathymodiolus spp. was identified from this vent field.

During the following two days, a detailed mapping program (848 nautical miles) was carried out on the way to the next working area at the Monowai Seamount on the northern end of the Kermadec arc. Main purpose was the infill of existing gaps along the northern end of the Whakatane graben system and along the Kermadec arc. Our arrival at Monowai Seamount in the afternoon of May 1st was followed by the deployment of the SIMRAD CTD-probe in the Monowai caldera down to water depths of 1350 m in order to re-calibrate the SIMRAD system. This was followed by two deployments of the gravity (wax) corer. These attempts resulted in limited sampling success, related to the hydrophilic nature of the used vaseline. The first ROPOS dive at the active summit of Monowai (R1041) started early in the morning on 02 May. As the drop point was approached, audible "bumping" of the ship and visible discoloration and upwelling at the surface was noted in several places, most likely related to steam explosions from a small cone building on the southern flank of the summit. The ROV landed at about 3350 m depth and climbed up the debris slope toward the active cone.

Visibility was significantly reduced owing to continuous turbidity currents shedding off the building cone. The dive was abandoned due to very poor visibility as the active cone was approached. In the afternoon, dive R1042 was deployed at the Eastern Wall of the Monowai Caldera between 1620 and 615 m water depths. This dive surveyed the base of the original constructional edifice of the Monowai volcanic complex as exposed in the deepest part of the eastern caldera wall. The eastern wall exposes a stepped slope of massive basalt with visible pillows, slopes covered by blocky talus of massive basalt, coherent flow material and bedded volcaniclastic material covered by fresh scoria and black sand with possible sills of more massive coherent material. The ROPOS dive was followed by five TV-grabs on the rims and the resurgent dome(s) within the Monowai caldera. The mapping program focused on the bathymetry west of Monowai Seamount and aimed at the study of the regional structural setting. Dive R1043 was conducted at Mussel Ridge, a linear outcrop of massive coherent basalt, heavily encrusted by mussels. Here, low-temperature vents were identified during PISCES dives in 2005. Numerous areas of venting were located at a depth of about 1152 m and dense coverage of mussels were mapped on the flank and along the northwest trending summit of Mussel Ridge. Several sulphur chimneys and tube worm clusters were observed. Vents at 15°, 24°, 30° and 39°C were located and sampled (fluids and fauna). TV-grab operations recovered altered and brecciated aphanitic basaltic lava, sulphur- and clay-cemented volcaniclastics, and layers of native sulphur. Dive R1044 in the morning of 4 May was dropped in the vent biota field on the flank of Mussel Ridge for fluid and fauna sampling purposes. A CTD probe was deployed for water sampling purposes. The total number of organisms recorded from ROPOS dives numbered 297. TV-grabs produced 628 individual specimen samples. Key findings included the vent mussel Bathymodiolus sp. and the tube worm Lamellibrachia spp.

Dive R1045 was dropped in the summit crater of the arc volcano immediately north of Monowai at 25°S in the afternoon on 4 May. The survey of the geology of the inner caldera wall revealed a swarm of dikes up to 300 m thick with screens of weakly bedded coarse volcaniclastic material at the base at 700 m depth. The dikes die out toward the top of the caldera wall and the uppermost part of the wall (above 365 m water depth) consists of unconsolidated ash and lapilli. Sampling recovered plagioclase-pyroxene phyric and slightly vesicular basaltic lava. There are no indications for hydrothermal activity. In between a small mapping program, a CTD was deployed in a water depth of 1623 m. This arc volcano appeared devoid of macrofauna.

The next diving and sampling target was the so-called Volcano 19 about 80 miles to the north. The transit was used for compiling additional bathymetric lines in the transition area between the northernmost Kermadec arc and the southernmost Tonga arc segment. Before breakfast on May 5th, a CTD was deployed for a sound velocity profile for SIMRAD calibration. The following ROPOS dive R1046 focused first on large caldera structure on the western side of volcano 19. The first part of R1046 surveyed the field of Fe-oxide chimneys and low-temperature vents along the base of the south wall of the Western Caldera. A 112 °C vent that was measured in 2005 during SITKAP was relocated at the center of the Fe-oxide chimney field. Water, gas, and hydrothermal precipitates were sampled at this location, together with samples of bacterially precipitated Fe-oxides. Lower-temperature Fe-oxide chimneys were surveyed to the east of this location. The second part of the dive surveyed the southern area of venting at the summit cone of Volcano 19. This part of the summit cone complex is covered by a large area of hydrothermally cemented ash. A site for the study of vent fauna and the rare flat fish Symphurus spp. was located among sulphur-cemented ash at the southern edge of this field. The night program included the deployment of four TV-grabs in the Western Caldera. A variety of weakly consolidated, hydrothermally indurated volcanic ash, soft Fe-oxyhydroxide chimney fragments, glassy basaltic volcanic bombs, vesicular phyric and glassy aphyric lava was sampled. Additional 44 nautical miles were mapped during the second half of the night.

Dive R1047 was dropped in the summit cone complex of Volcano 19 on May 6th. Fish traps were deployed at the southern end of the summit cone complex and a survey was conducted in the area of the clam field in the depression on the southwest flank of the summit complex. A temperature of 270°C was measured in the two-phase vent located originally in 2005. High temperature fluids were sampled at this location and at a large barite chimney at the summit of the cone complex. The vent fauna was kept undisturbed for the next dive. The night program focused on bathymetric mapping of the surroundings of Volcano 19 (97 nautical miles). A CTD cast down to 1012 m in the western caldera was carried out in the morning of 7 May. The following dive R1048 was deployed in the summit cone complex again. It was devoted to sampling vent fauna and water at high-temperature vents around the large barite chimney at the summit. Chimney samples were collected. The fish traps were recovered successfully and samples of bacterially precipitated Fe-oxides were taken from the Fe-oxide chimneys at the western flank of the cone complex. An approaching low only allowed two more TV-grab stations. Samples recovered included several pieces of intermediate to highly altered volcaniclastic material and volcanic fragments, chimney fragments with sulphide mineralization, two fragments of anhydrite chimneys with sulphide enrichments lining (wurtzite, galena, pyrite) in the center and an outer rim of As sulphides. A total of 268 organisms were sampled using ROPOS and these included several unidentified clams as well as a lucinid.

Further operations at Volcano 19 were abandoned due to an approaching low and operations were moved to the North to the southernmost Valu Fa ridge (Hine Hina site) in the southern Lau basin. The transit to escape a gale was used for an ambitious mapping program in the area where the Tonga island arc and the Lau basin approach to within 40 km (333 nautical miles). The weather conditions improved only slightly and the following day May 9th only allowed bathymetric mapping which was set up to supplement the lines from the SO-167 campaign (160 nautical miles). The Hine Hina field in the Lau Basin adjacent to Volcano 8 was last visited in 1991 by the submersible Nautile and photographed during an OFOS survey in 1998 during SO-167.

A CTD cast was carried out for a sound velocity profile in the morning of May 10th. Dive R1049 was deployed at the SO-167 OFOS track and located the French marker #98 in a field of mussels on a flank pillow cone adjacent to the main ridge segment. Pyrite and barite encrusted pinnacles of ash were located in areas where chimneys were reported. One area of relict chimneys was found at the southeast end of the ridge segment in an area where Nautile had recovered stockwork mineralization. A survey of the mussel field on the adjacent pillow cone was conducted prior to the end of the dive. Massive blocks of Cu-rich sulphides from relict chimneys were sampled by ROPOS and by a subsequent TV-grab station at this site. Fauna comprised two species of Bathymodiolus vent mussels, a large limpet species, and squat lobsters. Good sampling success and improving weather conditions allowed the return to the original program.

An eight hour transit brought us back to the Tonga island arc. The operations continued on May 11th at Volcano 1 (cf. SO-167). After a morning CTD sampling cast down to 416 m, ROPOS dive R1050 was dropped at a chain of three little craters which were identified during SITKAP 2005 Pisces dives to host active hydrothermal venting. This dive was used to locate and survey the mussel field and gas vents. R1050 located the main field at marker #43. A semi-continuous field of mussels and gas venting was mapped along the southern edges of the easternmost and central pit craters. Venting at a maximum temperature of 70° C was found at two locations, but the high-temperature (151° C) vents measured in 2005 (marker #41) could not be found despite an extensive survey. The impression was that the volume of gas and the temperature of the vents noted during the PISCES dives had decreased since 2005. An area of abundant flatfish was surveyed on the north flank of the scoria cone adjacent to the chain of craters. After the eight hours dive, three TV-grabs were deployed on the flanks of Volcano 1 for volcanological and petrogenetic studies. Two grabs recovered basaltic vesicular, aphyric and partly glassy lavas. A mapping program enlarging the bathymetry around Volcano 1 (77 nautical miles) was carried out for the rest of the night.

On May 12, ROPOS dive R1051 focused on the chain of craters and the flank of a young scoria cone to the Northwest. The morning dive started at the westernmost pit crater in the chain of craters and continued to the summit of the scoria cone south of the chain. A survey of the western end of the central pit crater found a large area of Fe-oxide encrusted ash (>60 m diameter) with abundant bacterial floc, which was sampled for studies of Fe-oxidizing bacteria. No evidence of venting was found in the westernmost pit crater. A survey up the flank of the scoria cone south of the mussel field found patches of white bacterial mat and isolated patches of mussels on cemented ash blocks near the summit (100 m depth). In the afternoon, the dive surveyed the sector collapse on the flank of Volcano 1 from a depth of 600 m up to the top of the northwest scoria cone. A massive pillowed unit occurs at the deepest exposure in the scar of the sector collapse, revealing the interior of the basal section of Volcano 1. The remainder of this section comprises a steeply dipping dike complex about 150 m thick, which grades upward into a block-rich to fine volcaniclastic sequence. White altered clasts were observed only in the lower part of the volcaniclastic sequence. The base of the scoria cone from 450 m to 350 m consists of blocky to coarse volcaniclastics intruded by numerous dikes. The upper part of the cone is covered by unconsolidated scoria, cinders, and local bombs. At the summit of the cone, near 100 m depth, large blocks covered by bacteria were observed. These may be the remnants of a dome at the top of the cone. The final leg of the dive examined a section of the lower part of the linear ridge (elongate scoria cone) northwest of the chain of craters. The dive was followed in the evening and first half of the night by four TV-grabs. The grabs aimed at the sampling of hydrothermal precipitates from the mussel fields and gas vents. Two successful grabs recovered several samples of strongly altered volcaniclastic rocks with more massive layers and crusts of very fine-grained pyrite and fine- to coarse-grained precipitates of native sulphur in vesicles and interbedded with ash layers. The mapping program (83 nautical miles) was continued for the rest of the night.

In the morning of May 13th, a CTD sampling cast was carried out above the mussel field close to the southern cone. Dive R1052 aimed at the survey of three 250 m high caldera wall sections at the eastern and southeastern inner caldera wall. Two sections of the eastern wall, 500 m apart, revealed massive coherent basalt (dike or sill complex) at the base (450 m depth). A bedded volcaniclastic unit was observed above the coherent base in both sections, capped by a thin section of finely bedded tuff. Above 400 m depth, the caldera wall is dominated by weakly bedded volcaniclastic units with abundant, densely packed (locally reversely graded) lithic blocks. The entire section of block-rich volcaniclastic material is cut by numerous dikes subparallel to the caldera wall. A third section of the southeastern caldera wall revealed a different stratigraphy dominated by a massive, columnar-jointed coherent dike and sill complex from 400 m depth to the top of the caldera wall at <200 m. Sampling collected a decent stratigraphic suite of the caldera wall including a variety of andesitic to dacitic porphyritic to aphyric lava flows, massive dikes and sills, and volcanic ash. After the 10-hours dive, four TV-grabs were carried out to supplement the volcanic stratigraphy along the rims of the caldera wall and at volcanic ridges. The mapping program at night (39 nautical miles) enlarged the surroundings of volcano 1 towards the North.

In the morning of May 14th, the water sampling program was finished by a CTD cast above sulphur-rich vents and associated precipitates up the flank of the scoria cone south of the mussel field in a water depth of 198 m. Dive R1053 was deployed at the cone south of the chain of craters and continued to the NW flank of the scoria cone south of the mussel beds. This dive concentrated on the shallow-water occurrences of mussels on the top of the two scoria cones on the flank of Volcano 1. The first part of the dive was at the summit of the scoria cone on the NW flank of the Volcano. A detailed survey was carried out of the mussel beds that occur on areas of sulphur-cemented ash near the summit (100 m). A survey of biology at the peak (64 m) was also conducted. The second part of the dive focused on the smaller area of mussels at the top of the scoria cone south of the main mussel field in the chain of craters. Detailed surveys of the mussels, algae, coral, etc. were carried out along with plankton tows and water-column filtering. The 7-hours dive ended with water sampling at the sulphur vent in the main mussel bed, gas sampling at marker 43, and suction sampling of Fe-oxides at the west end of the central pit. The fish traps deployed during a previous dive were recovered. Four TV-grabs supplemented the sampling at the mussel beds. Previous TV grabbing at the location of the sulphur vent recovered massive native sulphur crusts. Several pieces of lapilli ash, impregnated by native sulphur were sampled. Crusts of massive pyrite and marcasite with sulphur were recovered from the center of the mussel field (near marker #43). Several pieces of volcaniclastic material and vesicular, plagioclase-phyric lava, partly volcanic bombs, were sampled. Recovered fauna included high concentrations of bathymodiolid vent mussels along with small crabs and gastropods, and the flatfish Symphurus spp. Bathymetric mapping of the northern and western extension of volcano 1 (64 nautical miles) completed the night program.

The last ROPOS dive R1054 was deployed at the northern caldera wall of volcano 1 on May 15th. This dive consisted of two sections of the lower caldera wall. The lower section in both parts (between 480 m and 380 m) consists of a finely bedded sediment unit more than 100 m thick, cut by rare dikes. This unit is overlain by the mass flow units observed in other sections of the caldera wall. The second part of the dive inspected the top of the linear ridge adjacent to the two scoria cones on the south side of the caldera. This was the location of a TV grab that recovered fresh volcanic bombs. Two successions of scoriaceous material were observed. The linear ridge may represent a series of overlapping cinder cones developed along the length of an eruptive fissure, possibly similar to the feature on which the chain of craters is located. There is no evidence of recent hydrothermal activity or degassing. The scientific program finished with a bathymetric line (25 nautical miles) on the departure to Suva/Fiji. The MANGO program was completed at 17:00 on 15 May and RV SONNE then sailed for Suva where it arrives in the morning on May 17th. All samples and equipment, and ROPOS equipment were packed into the container ready for offloading in port. Containers were offloaded the same and the following day and the scientific party progressively disembarked on May 18th. The scientific crew boarded RV SONNE on the 19th and sailed in the morning of May 20th for cruise SO-192 MANIHIKI.

5 STRUCTURE, BATHYMETRY AND SAMPLING OF THE TONGA-KERMADEC ARC

Ulrich Schwarz-Schampera, Mark Hannington, Harold Gibson, Karsten Haase, Wolfgang Hirdes, Mike Hocking, Julia Rutkowski, and ROPOS Team

5.1 Objectives of the Tonga-Kermadec Arc Hydrothermal and Volcanological Program

The Tonga-Kermadec Trench is a classic example of an immature, intra-oceanic, convergent margin where Pacific Plate lithosphere is subducted beneath a volcanic island arc chain. The extensional back-arc and southwards propagating Lau Basin and Havre Trough separate the Tonga (or Tofua) and Kermadec volcanic arcs from the remnant Lau and Colville volcanic arcs. The plate margin lacks evidence for remnants of continental crust and is inferred to be entirely oceanic, with the exception of the southernmost Kermadec arc.

The study area encompasses a series of volcanic seamounts on the ~2,500 km Tonga-Kermadec chain. The area is divided into two main parts: the Tonga arc in the north (from 16°S to 27°S, ~1300 km long) and the Kermadec arc in the south (from 27°S to 38°S to 38°S, ~1200 km long). There are at least 94 volcanoes along the length of the arc, spaced ~30 km apart. The Tonga arc includes 41 volcanoes, with summit depths ranging from 1,200 to <100m. The Kermadec arc includes 33 submarine volcanoes, with depths ranging from 1,700 m to 200 m. The volcanoes are situated 40-70 km west of the fore-arc bulge (Kermadec Ridge in the south arc and Tonga Ridge in the north) and 180 km west of the deepest point in the southern hemisphere (Horizon Deep) in the Tonga Trench. Subaerial volcanoes along the arc include the Kermadec islands (between 29°15'S and 30°30'S), ~940 km NE of New Zealand, and the Tongan islands (e.g., Ata island at 22°30'S, 170 km south of Tongatapu). The submarine volcanoes are simple cones, with basal diameters of ~30 km and heights of 1 to 2 km above the surrounding sea floor. One third of the volcanoes have summit calderas, the largest being 5 km in diameter. Most calderas occur at water depths of <1,000 m, and many are host to active hydrothermal vents or centers of volcanic degassing, with more than half of the volcanoes surveyed venting hot plumes into the ocean. The cruise aims at the examination of a number of volcanoes from 21°S (Volcano 1) to 25°S (Volcano 19), a large volcanic cone and nearby caldera complex in the transition zone between the southern end of the Tonga arc and the northern end of the Kermadec arc (Monowai volcano at 26°S), and at the study of vent fields on the continental shelf of New Zealand offshore the Taupo volcanic zone (Calypso vent fields, ~37°40`S).

SO-192/2 examines and samples submarine hydrothermal vents, seafloor mineralization, fauna, and recent volcanic formations along the Tonga-Kermadec arc. This unique area includes some of the largest and most active submarine volcanoes of the western Pacific, as well as one of the largest and deepest submarine calderas. The focus of the expedition will be on exploration of previously unmapped volcanic centers over a range of water depths from 1500 to <100 m. Key questions that will be addressed include the link between regional tectonics and the volcanic history of intra-oceanic arcs and how massive volcanic degassing is affecting the local environment, associated mineral deposits, and vent fauna.

The principal activity of the expedition is mapping and characterization of the seafloor in the summit areas of the target volcanoes, to identify areas of recent volcanic activity, hydrothermal venting, and patterns of pelagic and benthic ecosystem structure and function. This work includes (i) SIMRAD multibeam bathymetric mapping, (ii) camera surveys (video compilations and digital photographic mapping of the seafloor), (iii) water-column sampling using towed CTD, (iv) collecting of volcanic rocks using the submersible and TV-guided grabs, (v) collection of hot water and gases from active hydrothermal vents, (vi) collection of hydrothermal precipitates, and (vii) limited macrofaunal collection in the vent areas. The majority of sampling is done with ROPOS.

The BMBF-funded research will focus on petrology and tectonics, geochemistry of the arc magmas, hydrothermal precipitates, hydrothermal fluid chemistry, and organic geochemistry. We address (i) along-strike variability in the structure of the arc (e.g., in response to subduction of the Louisville Ridge and spreading in the nearby Lau back-arc basin), (ii) the influence of subducted sediments in the geochemistry of arc magmas, (iii) the significance of diverse lavatypes (basalt to andesite and dacite) at the different volcanic centers, (iv) the input of magmatic volatiles in vent fluids, (v) hydrothermal mineralization and alteration with the mineralogical and geochemical characterization of the hydrothermal precipitates, (vi) origin, size and dimension of hydrothermal venting in arc systems, (vii) vent biology, and (viii) physical volcanology of the arc stratovolcanoes.

5.2 Bay of Plenty, Southwest White Island, Calypso Vent Sites (37°35`- 37°45`S)

5.2.1 Bathymetry and Structure

The outer Bay of Plenty continental shelf, southwest of the active White Island volcano, forms a region of known submarine hydrothermal venting with observations of gas bubbling, metalliferous sediments, and anhydrite mounds (e.g., Duncan and Pantin, 1966; Glasby 1975; Lyon et al., 1977; Sanaro et al. 1989; Pantin and Wright, 1994; Stoffers et al. 1999a,b). The known sites of most vigorous hydrothermal venting (including the Calypso vent) occur within the offshore segment of the Whakatane Graben, a zone of late Quaternary extensional tectonics associated with winding of the Taupo Volcanic Zone. Pantin and Wright (1994) have suggested the hydrothermal vent sites are associated with active normal faults in the Whakatane Graben. Multibeam mapping during SO 135 cruise (Stoffers et al., 1999) revealed the outer Bay of Plenty area between 150 and 200 m water depth comprising a broadly undulating, seaward dipping continental shelf that is disturbed by a series of fault striking 044°-053°. At least four fault systems (including the White Island Fault Zone) can be observed within the mapping data. Typically, the faults have seafloor expression comprising circular-elongate depressions, tilted blocks, and raised ridges, all of which have vertical relief of 5-20 m. The faults appear to be segmented over strike lengths of 5-7 km. On the upper continental slope, seafloor expression of the fault is less pronounced, although locally they can be identified to water depths of 240 m (Stoffers et al., 1999, Robertson, 1999).

Three major hydrothermal vent site areas, initially identified by acoustic backscattering from columnar bubble zones streaming to the sea-surface are identified at 37°41.7`S, 177°06`E; 37°41.3`S, 177°07.4`E; 37°35.8`S, 177°06.2`E (the Calypso vent). Smaller vent sites occur in an area centered at 37°35`S, 177°06.6`E (Stoffers et al., 1999).

About 360 additional line kilometers of bathymetric mapping was conducted with the SIMRAD system during the nights following ROPOS and TV-grab operations. The combined surveyed area from SO-135 and SO-192 covers an area of approximately 300 km^2 southwest of White Island (Figs. 5.1 and 5.2). The mapped area has gentle relief with a relatively flat, undulating surface between approximately 150 and 200m water depths. The northeast and eastern margins of the mapped area dip steeply to deeper water depth.

Northeast trending structures are evident throughout the entire map area. These features are several hundred meters wide, have tens of meters of relief, and extend for several kilometers across the mapped area. Circular depressions are observed at the termination of several of these features; this may be an artefact of sedimentation. These features are believed to represent northeast trending normal faults developed during Quaternary extension (Pantin and Wright, 1994). This northeast trending structural pattern pervades in the fore-arc volcanoes along the Kermadec Arc.

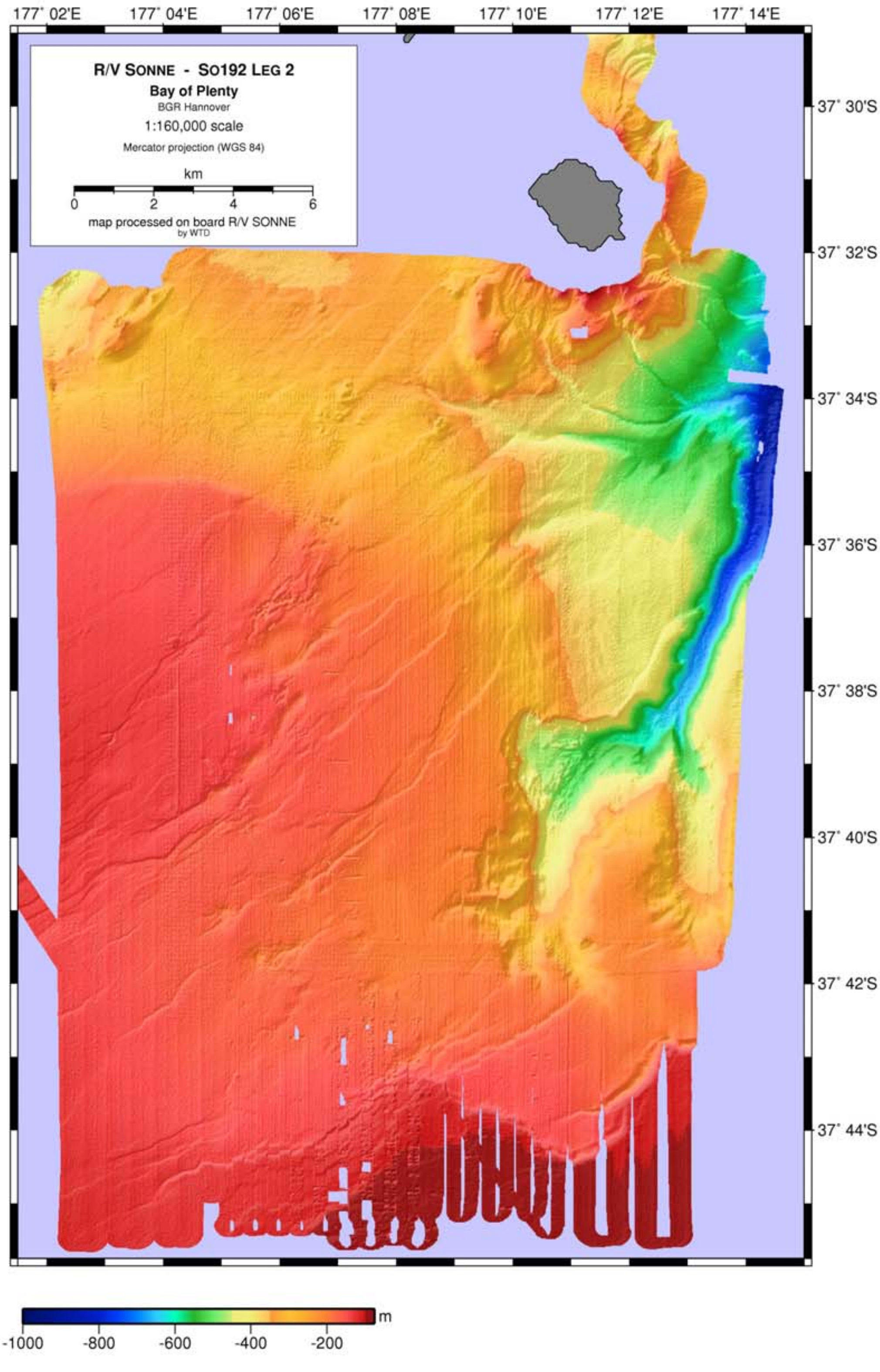


Fig. 5.1: Bathymetric map of Calypso Vent area in Bay of Plenty, southern Kermadec arc.

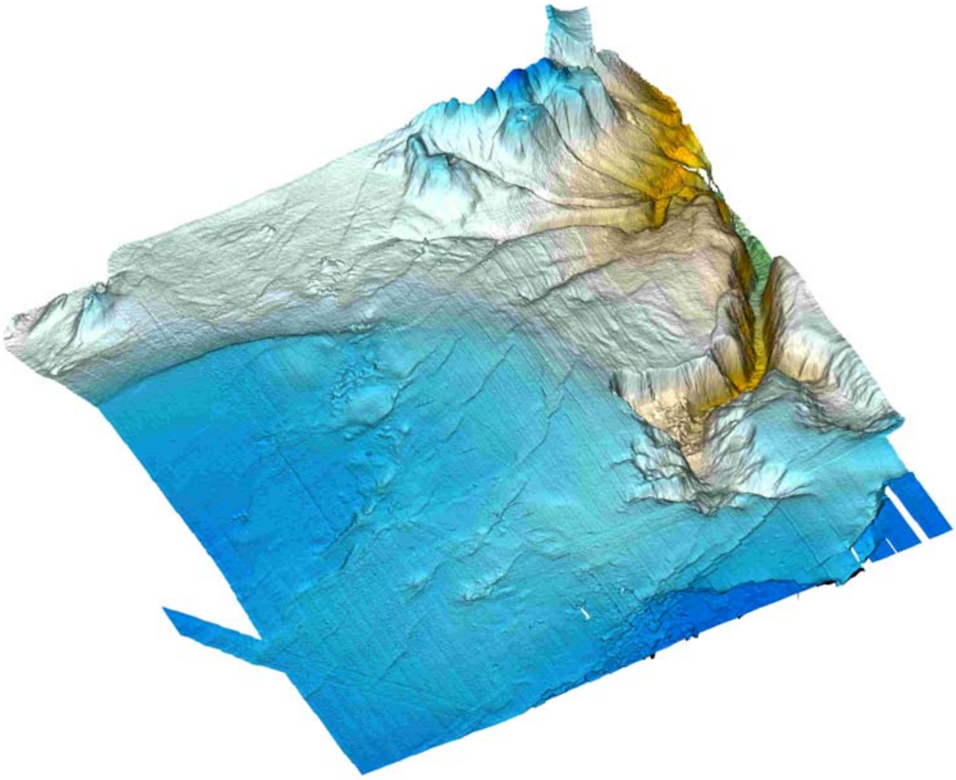


Fig. 5.2: 3-D bathymetric map of Calypso Vent area in Bay of Plenty (view from SW to NE; refer to Fig. 5.1 for latitude and longitude positions).

Calypso Hydrothermal Field

The Calypso Hydrothermal Field consists of three sites of hydrothermal venting located on the continental shelf approximately 10-15 km southwest of White Island in the northern extension of the Taupo Volcanic Zone. Previous workers in the area observed rising bubble plumes and recovered hydrothermally altered mud indicating the presence of a seafloor hydrothermal system (Duncan and Pantin, 1969; Glasby, 1971; Sarano et al., 1989; Pantin and Wright, 1994). Analysis of fluid samples collected during SO-135 indicated the primary gas phase in the hydrothermal fluid is CO_2 with minor H_2S. Hydrocarbons contained within the fluids are derived from hydrothermal distillation of organic matter in the underlying sedimentary sequences (Botz et al., 2001). A detailed study of alteration mineral phases indicates that venting of hydrothermal fluid through the volcaniclastic material has led to a varied and geographically distinct assemblage of alteration mineral phases.

The North Vent Field (NVF) is the original site of hydrothermal venting reported at Calypso. Weakly lithified volcaniclastic material recovered from this site has been primarily altered to montmorillonite, minor mixed layer clays and talc. Native sulphur is spatially associated with the pervasively clay-altered samples, and is observed cementing volcaniclastic particles and filling primary pore spaces. Anhydrite mounds were also recovered from the NVF.

The principal hydrothermal alteration phase at the Southeast Vent Field (SEVF) and the Southwest Vent Field (SWVF) is amorphous silica which has filled the pore spaces between volcaniclastic particles, and has overprinted early barite, minor clay, and native sulphur mineral phases. Cinnabar, stibnite, and amorphous arsenic sulphides form crusts on the outer surfaces of the samples, fill fractures, and occur as inclusions within pyrite-silica veins. Clay-altered, sulphur-rich samples were recovered from the Southeast and Southwest Vent Fields (SEVF, SWVF) but are volumetrically subordinate to the silica alteration facies. Several volcaniclastic samples from this site contained liquid hydrocarbon and charcoal fragments. A similar juxtaposition of alteration phases is observed in active geothermal environments in the subaerial portion of the TVZ (e.g. Waiotapu; Hedenquist and Browne, 1989; Broadlands-Ohaaki; Simmons and Browne, 2000).

5.2.2 ROPOS Operations

The ROPOS submersible was used to make seafloor observations and collect samples on two dives at the Calypso Hydrothermal Field. Dive SO-192-2-R1039 was the first dive of the cruise and surveyed the Southwest Vent Field. The dive commenced at the southwestern end of the vent field at 37º 41.65 S 177º 05.60E in a circular depression. The bottom in this area is a heavily sedimented boulder field with subdued topography. Uplifted blocks, up to 1m in relief, were observed along the margins of the depression. Three vent sites were observed in this area associated with well-indurated, layered blocks, believed to be hydrothermally altered ash (Fig. 5.3). Venting was characterized by bubble streams and shimmering water surrounded by mats of white bacteria up to 5m in diameter. The dive progressed along the south wall of the northeast trending structure at a heading of 070 towards the Southeast (Mercury) Vent Field. Very localized bubble streams were observed along the fault. A cluster of vents (V4-8) was located in and around two 150-m diameter depressions marking the northeast end of the linear fault zone. The vents occur in areas of broken slabs of, uplifted and jumbled, cemented-ash, marking the edges of the depression between 189 and 198 m depth. Small patches of mussels were found at one vent (near V4). Other vents consisted of bacterial mat, bubble streams, and sulphur-cemented ash. The area north and south of the depressions is covered by sediment. The northeast trending structures represent normal faults which provide conduits for hydrothermal fluid flow (Pantin and Wright, 1994). Collapse of the graben walls is reflected by the presence of layered-ash blocks. Hydrothermal vent sites were typically associated with white bacterial mats and an increase in the number of anemones. Corals, worms, and sponges were found near areas of shimmering water and bubble stream. Common roughy, tarakihi, cucumber, and king fish, as well as carpet shark, and conger eel, were also observed during the dive.

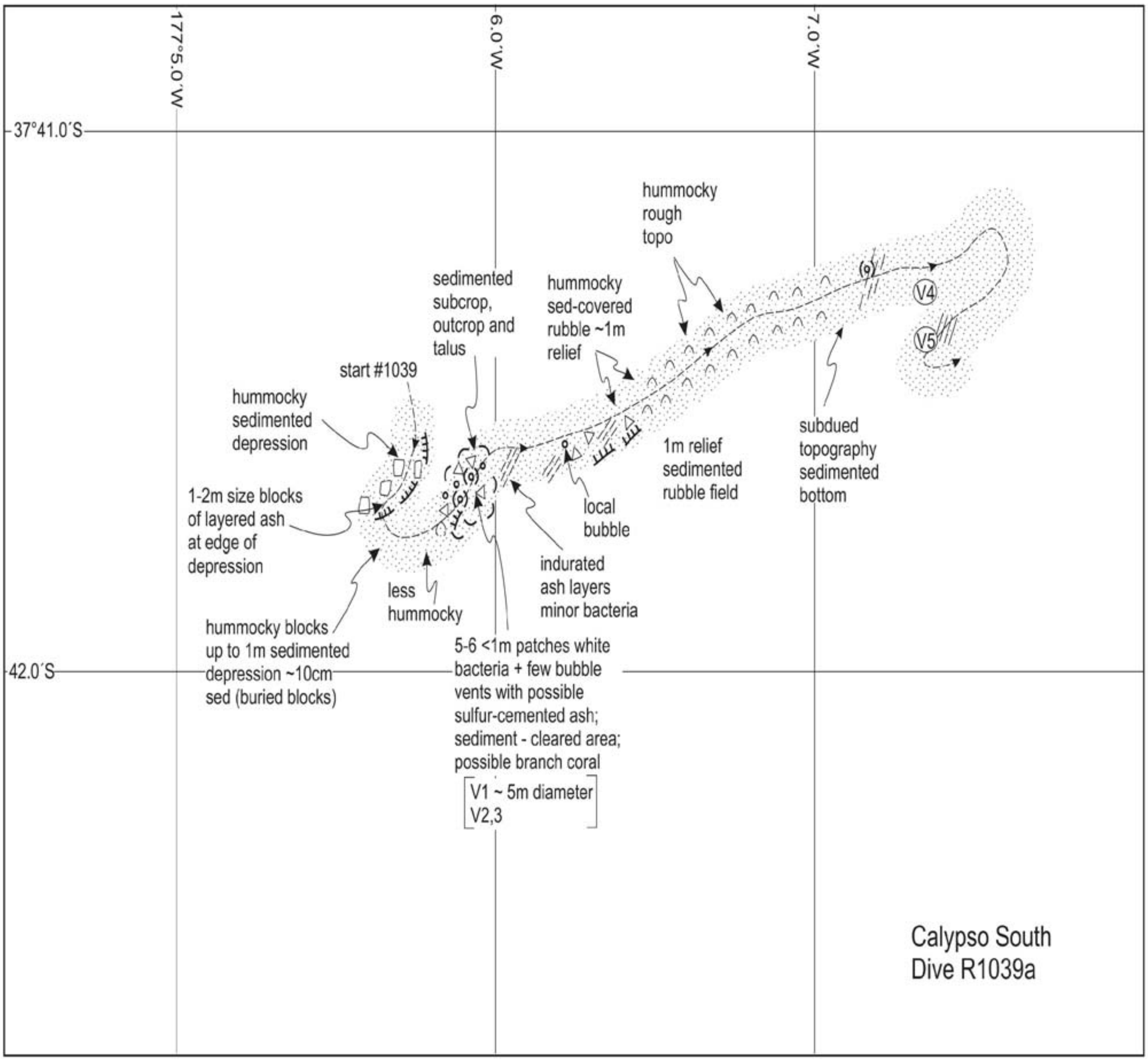
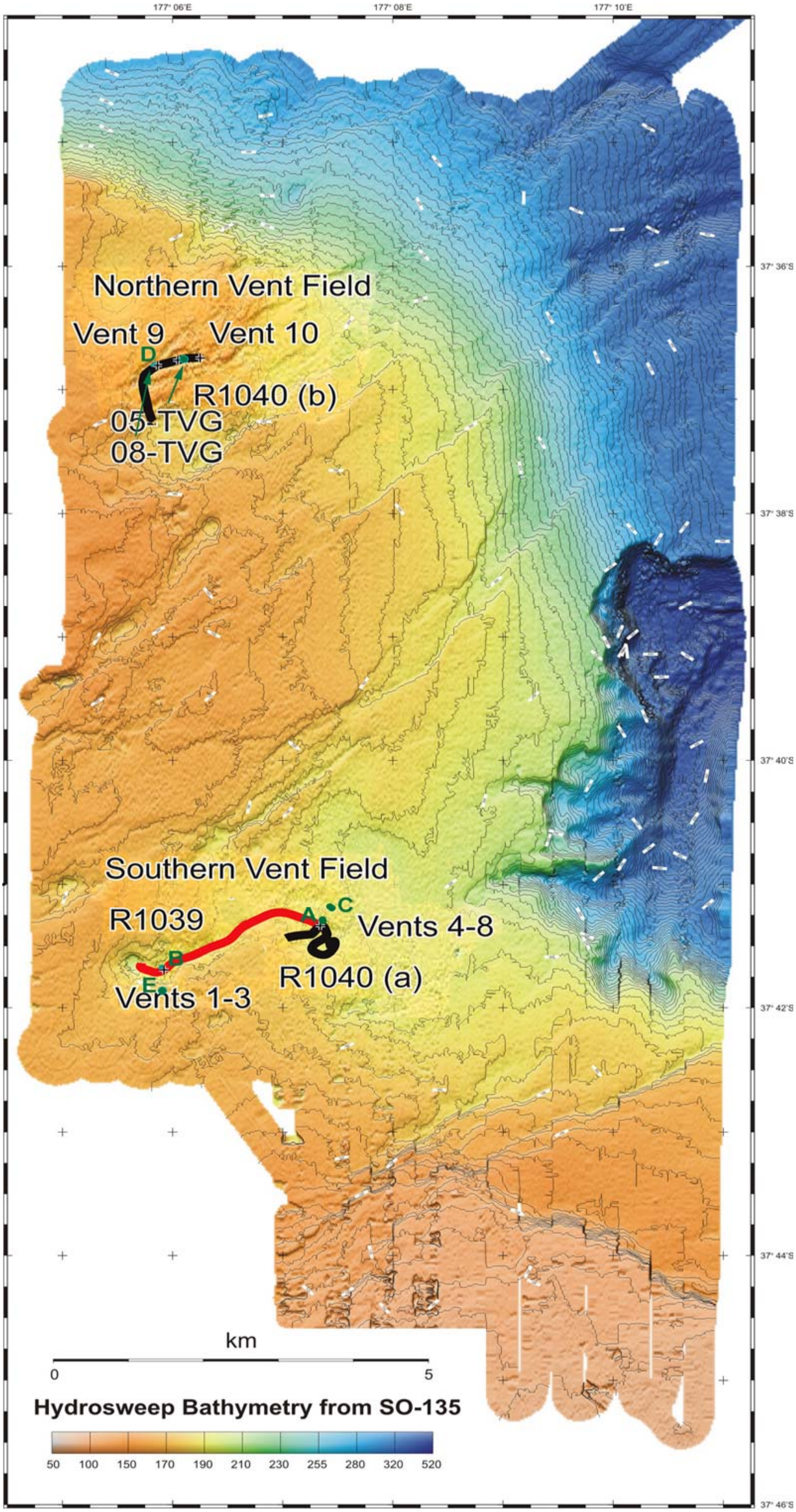


Fig. 5.3: Geological map of Calypso Southern Vent Field, Bay of Plenty, dive R1039 (vents 1-3).

The second dive, R1040, was conducted at both the Southwest and the Northern vent fields (Figs. 5.4, 5.7). The first part of the dive surveyed the Southwest Vent Field at the locations of V4 in the northeastern depression. Water and gas samples were collected at the location of V4. The second part of this dive was conducted in the Northern Vent Field in a series of northeast-trending depressions (Fig. 5.5; 5.6). It started at the southeast end of the field in hummocky sediment-covered blocks (uplifted blocks of cemented ash marking the fault zone). The sedimented surface often appeared pockmarked by the presence of numerous shrimp burrows. The first vents (V9) were located at the northeast edge of the westernmost depression. The main vent consists of a small area of bacterial mat, bubble streams and shimmering water, with notably red As-sulphide (realgar) in the cemented ash. A second vent (V10) was found in the northeastern depression along the fault. The vent consists of bubble streams among uplifted and broken slabs of sulphur-cemented ash (Fig. 5.8).



Samples
Bay of Plenty

A: R1039 0001-8
R1040 0004-10
04TVG

B: R1040 0001-3

C: R1040 0012/13

D: R1040 0014
08TVG

E: 07TVG

Fig. 5.4: Bathymetric map of the Calypso Vent area in the Bay of Plenty with tracks of ROPOS dives R1039 / R1040 and sampling locations of ROPOS and TVG samples.

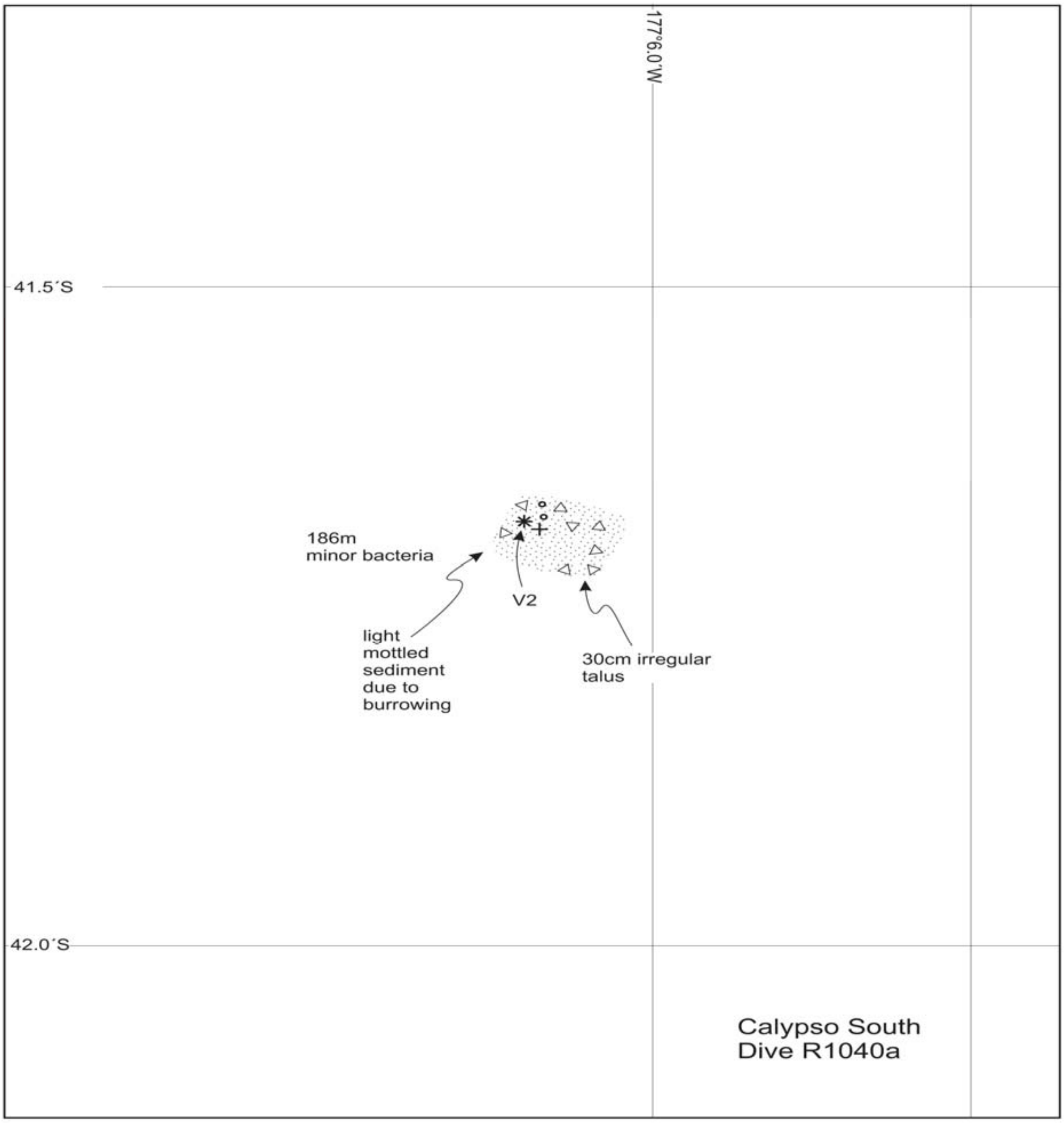


Fig. 5.5: Geological map of Calypso Southern Vent Field, vents 4 – 8, Bay of Plenty, dive R1040a.

Vent fauna at the North Vent Field was similar to that seen in the southern vent fields. Bacterial mats, anemone, and sponges were observed near sites of active venting. Sea perch, Lanter, and Tarakihi fish as well as a single Ray were present in the dive area.

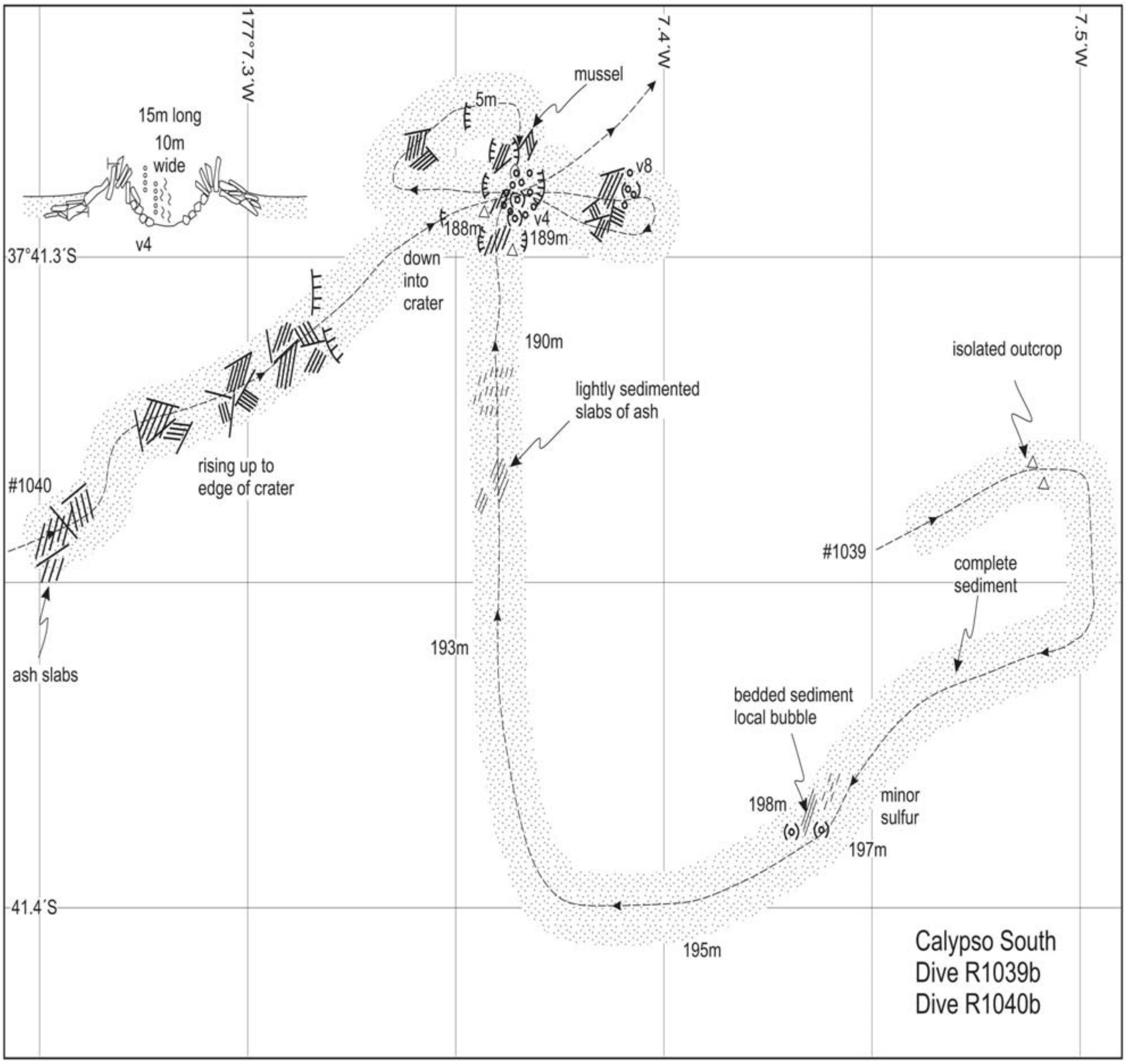


Fig. 5.6: Geological map of Calypso Southern Vent Field, vents 4 – 8, Bay of Plenty, dives R1039b (vents 1-3) and R1040a (vents 4-8).

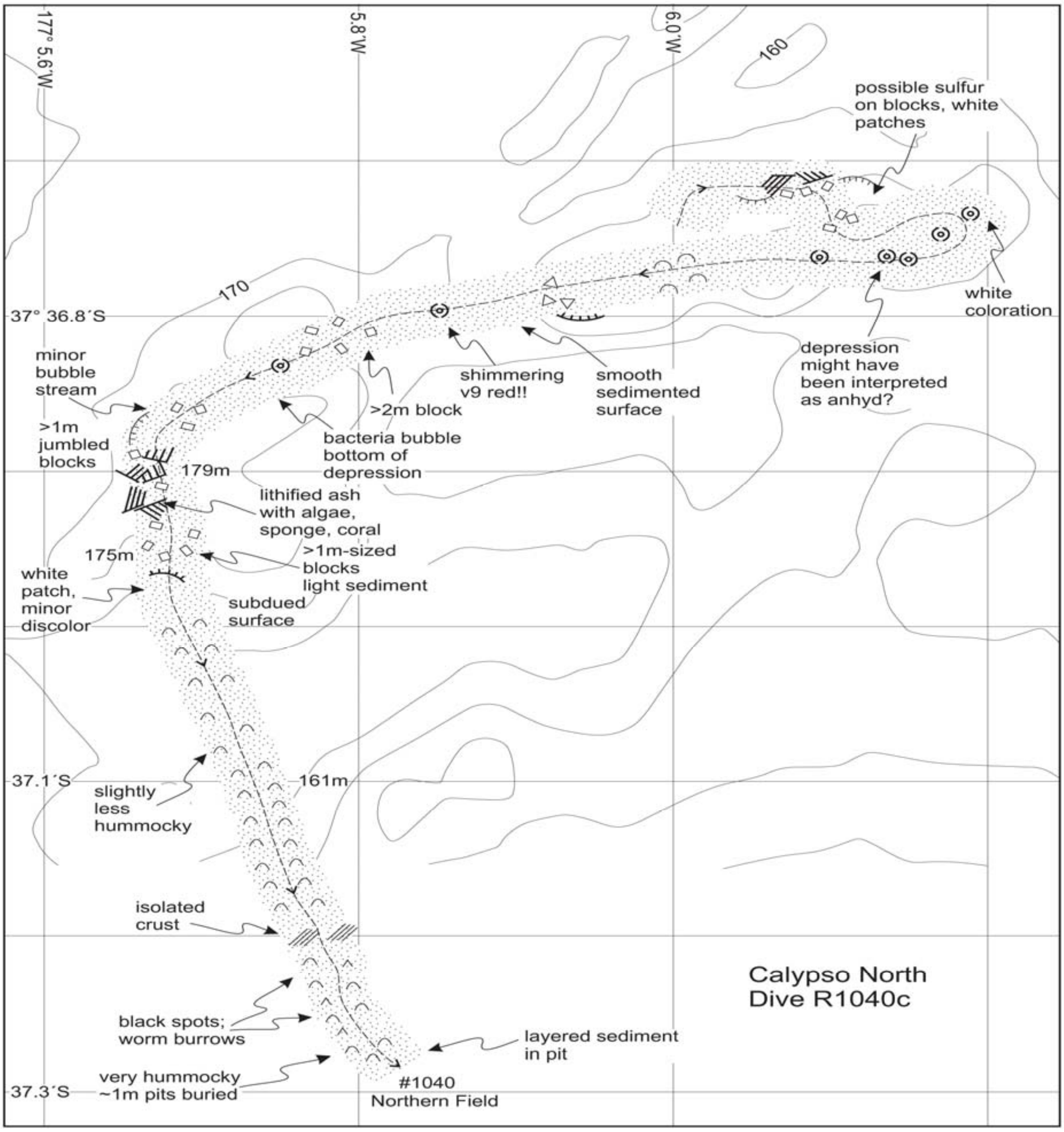


Fig. 5.7: Geological map of Calypso Northern Vent Field, dive R1040b (vents 9-10).

5.2.3 Sampling

Southern Vent Field

The Southern Vent Field was sampled during ROPOS dives R1039, R1040 and by station 04 TVG. Samples consist dominantly of ash-sized volcaniclastic material; layering was frequently observed. Several samples are dark in colour with a strong petroleum odour; these samples are believed to be impregnated with hydrocarbons. Native sulphur is present on the surface of a couple of samples. A single piece of massive anhydrite was recovered from a white mound during ROPOS dive R1040.

The TV-grab recovered a large volume of layered, pale grey ash. These samples were moderately well indurated with numerous tubes, believed to be shrimp burrows. Silica lines the margins of many of these conduits indicating that the bioturbation acted as a structural conduit for hydrothermal fluid flow. Weathering and removal of the least altered material created a network of interconnected silica tubes covered with pale grey ash creating a coral like appearance. The abundant volatile metal mineralization associated with intense silicification, recovered during SO-135, was not obtained.

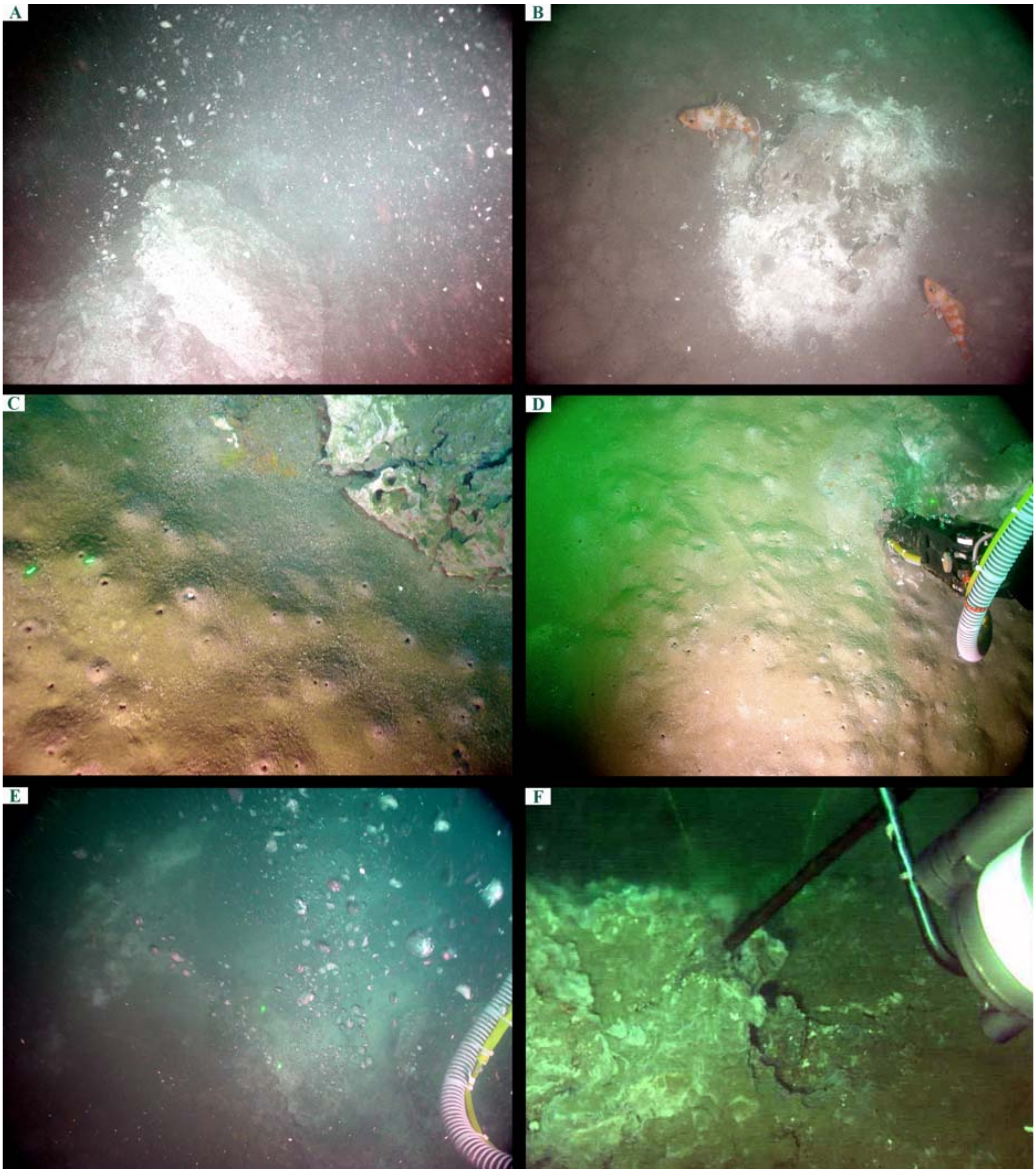


Fig. 5.8: Hydrothermal activity in the surroundings of the Calypso Vent field, Bay of Plenty, offshore Northern Island, New Zealand. A: Gas (CO_2) discharge at „Vent 4“. B: Fishes at a single vent site spot, approximately 60 cm in diameter. C: Pockmarked sediment with open vents from gas discharge. D: Fluid sampling of warm, shimmering water by suction sampler. E: Gas discharge and CO_2 bubbles at „Vent 4“. White spots represent living bacteria forming mats. F: Fluid sampling at „Vent 2“. Hydrothermal discharge is evidenced by shimmering water.

Northern Vent field

Rock samples were collected at the Northern Vent Field during 05TVG and 08TVG. A large volume of massive, layered, white anhydrite was recovered during 08TVG; the hot sample was still steaming at the surface. The anhydrite precipitation occurred on a quartz crystal ash substrate. Several samples display anhydrite cemented crystals inter-bedded with layers of massive anhydrite. A small patch of orange-red mineralization, possibly arsenic sulphide, was present on the surface of the few anhydrite blocks.

05TVG primarily recovered grey ash-sized volcaniclastic material; abundant native sulfur was present on the surface of many samples. Upon drying desiccation cracks were observed on the surfaces on many samples indicating the presence of possibly smectitic clays. Anhydrite was observed filling the pore spaces of a few dark grey ash samples. A single conglomerate sample containing clasts of ash sized material, cemented by native sulfur, was also recovered. One sample of unaltered pumice was present in the 05TVG sample.

5.3 Monowai Seamount (25°53`S, 177°11`W), Northern Kermadec Arc

5.3.1 Bathymetry and Structure

The Monowai Volcanic Complex (MVC; 25°53`S, 177°11`W) is an active submarine volcanic centre lying along the western margin of the Tonga-Kermadec ridge and arc front (Davey, 1980). It is located in the transition from the Kermadec to the Tonga segment of the arc, where Louisville Ridge (an old seamount chain on the Pacific Plate) is being subducted along the Tonga Trench. Volcanic activity was first reported in 1977 with the observation of discoloured water and vigorous gas emissions. A subsequent reconnaissance bathymetric survey and rock dredging established the edifice shoaled to ~120 m water depth, with single analysed rock comprising tholeiitic basalt (Brothers et al. 1980). The Volcanic complex consists of a symmetric cone with shoals to water depth of 98 m, and the Monowai caldera, an 11 x 8.5 km caldera ~7 km north-northeast of the summit (Fig. 5.9). This is one of the largest known submarine calderas and it is partially surrounded by an annular ring of basaltic to andesitic cones. The edifice is further one of the most active volcanoes in the Kermadec volcanic arc and activity on its large cone is dating back to the 1940s. Recently, it has been the repeated source of T-wave activity and submarine eruptions are reported frequently with particularly significant events in 1977, 1998, 2002, 2004, and 2005.

The Monowai Volcanic Complex (MVC) is built on a larger, low-relief basaltic-andesitic lava shield that rises above the seafloor and is located within a pronounced (approx 30 km wide) northeast-trending rift (Fig. 5.10). This Rift is a product of the NW-SE extension that has affected the MVC and transects the Kermadec arc at somewhat regular intervals along its entire length. A smaller basaltic cone (1 km basal diameter and height of 350 m) at a water depth of approximately 900 mbsl is located 2 km north of Monowai and near the margin of the Monowai caldera. Monowai and this smaller cone are the only two volcanic edifices that are not affected by the northeast-trending faults associated with the rift system.

Monowai Volcano

The Monowai Volcano is a basaltic cone that was likely constructed by a combination of magmatic and phreatomagmatic pyroclastic eruptions from a central, point-source vent with lesser volumes of basaltic lava, sills and dikes. The volcano has a basal diameter of 5 km and a height of approximately 900m. Lavas from the volcanic cone are basaltic (Fig. 5.11; Haase et al. 2002). The most recent eruptions at Monowai are characterized by plagiolcase (pyroxene) porphyritic (15% plagiolcase) basalt (basaltic-andesite; Graham et al., 2007). The volcano is active and is one of the three most historically active volcanoes of the Kermadec arc (Wright et al., 2007).

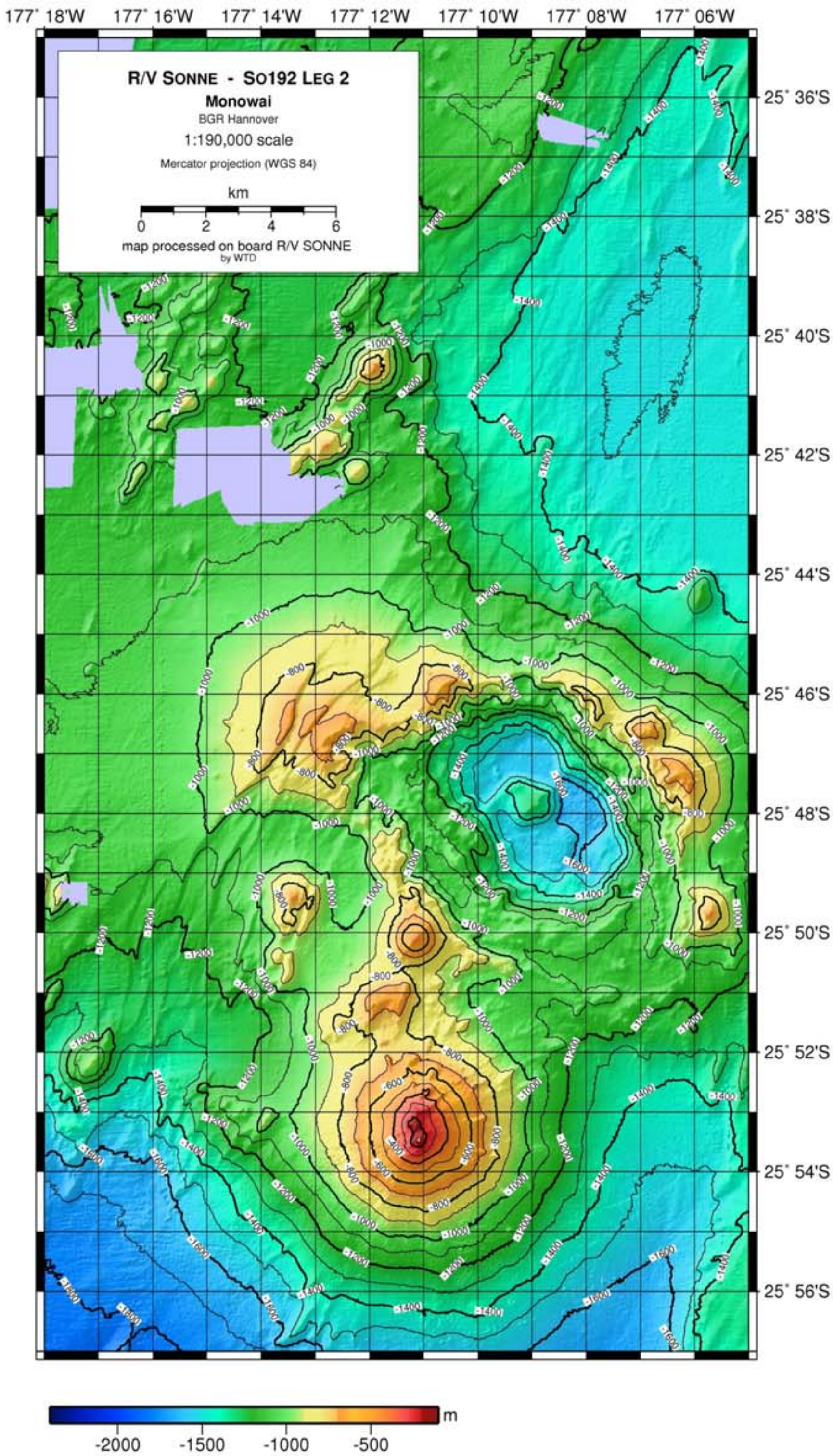


Fig. 5.9: Bathymetric map of the Monowai Volcanic Complex and surrounding areas, northern Kermadec arc. The MVC is located within a pronounced northeast-trending rift that transects the northern Kermadec arc.

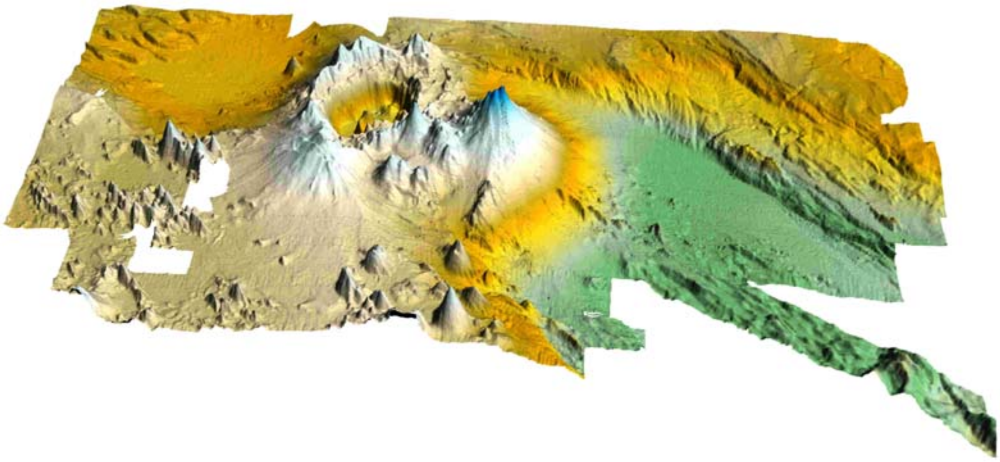


Fig. 5.10: 3-D bathymetric map of the Monowai Volcanic Complex (view from SW to NE; refer to Fig. 5.9 for latitude and longitude positions).

Chadwick et al. (2005) and Wright et al. (2007) describe changes in Monowai morphology between 1998 and 2004, probably followed the near summit eruption events between 2002 and 2004. According to map comparisons they inferred a collapse feature on the SE side of the volcano and a change in summit depth Monowai from 42 m below sealevel in 1998 to 132 m in 2004. A reconstructed cone within the slope of the failure scar has had a size of ~90 m in 2004. The new map from the SO-192/2 cruise shows that near summit eruptions over the past three years have completely infilled a radially oriented sector collapse scar and buried the reconstructed summit cone (Fig. 5.11). The recent summit at 98 mbsl has arisen ~40 m since this last mapping.

The volcano has an immature morphology and is capped by a steep-sided (13°-18°), unconsolidated pyroclastic cone. Pyroclastic eruptions during the initial stages of cone growth took place at a water depth of approximately 1000m to build a symmetric cone that is now <100 mbsl. Consistent angles of slope may reflect angles of repose for volcaniclastic detritus generated at volcano crest. The only significant morphological distribution to the flank slopes are a series of radial ridges centered on the crest that are interpreted as radial fissure dikes. Typically, these radial fissure dikes have relief of ~50 m above the surrounding flanks, but can be ~100 m (Stoffers et al, 1999). These fissure dikes are best represented on the mid-lower slopes, but individual dikes can be traced to the summit crest. Their subdued relief on the upper flanks probably reflects the presence of a covering mantle to volcaniclastic detritus with a source near the edifice crest. A series of three satellite edifices occur on the northern-northwestern flank of the main cone. A smaller basaltic cone (1 kilometer basal diameter and height of 350 m) at a water depth of approximately 900 mbsl is located 2 km north of Monowai and near the margin of the Monowai caldera. Monowai, and this smaller cone are the only two volcanic edifices that are not affected by northeast-trending faults, a product of the NW-SE extension that has affected the MVC and has produced northeast-trending rifts that transect the Kermadec arc at somewhat regular intervals along its length.

Stoffers et al. (1999) described diffuse low-temperature venting over a large part of the summit area, and suggested that the entire cone is inflated with warm hydrothermal fluid.

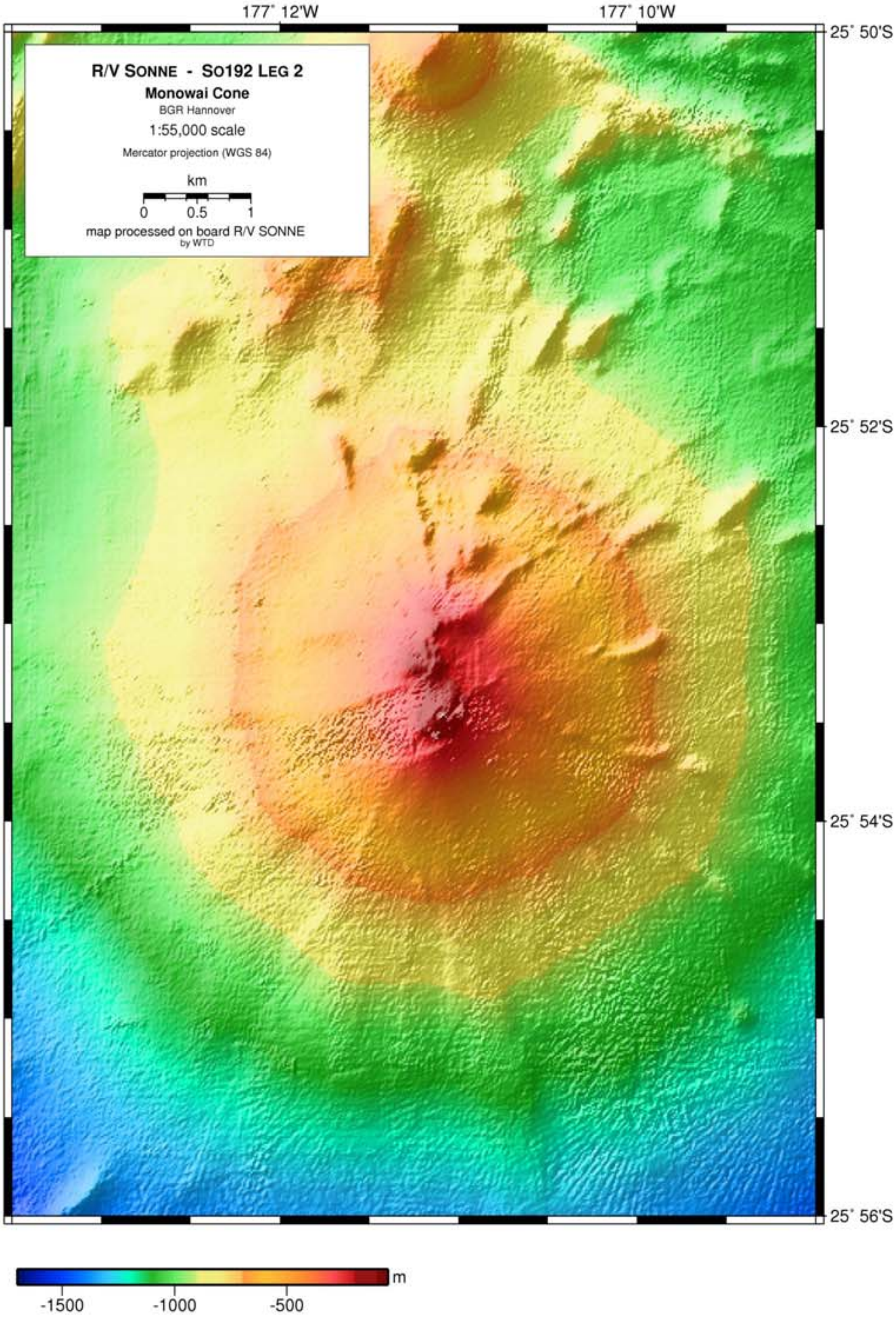


Fig. 5.11: Bathymetric map of the Monowai Volcano, MVC, northern Kermadec arc. Near summit eruptions have completely infilled a sector collapse scar over the past three years and buried the reconstructed summit cone.

Monowai Caldera

The most pronounced structural feature of the MVC is the north-northwest elongated (330˚) Monowai caldera that, based on topographic and not structural margins, has approximate dimensions of 10 km x 7 km (Figs. 5.9, 5.10). Structural cross-sections through the caldera indicate that caldera collapse was sequential, and asymmetric as indicated by the wider zone of subsidence along the northwest and southwest margins. The caldera rim occurs at a water depth of approximately 1000 mbsl and the caldera floor at a water depth of 1500 mbsl. The annular and continuous distribution of basaltic tephra deposits and cones along the southwest, northwest and northeast margins becomes discontinuous and less pronounced along the southeast margin, which suggests that in this area the caldera wall was breached by collapse into the caldera or down the southeast slope of the edifice. Individual cones within the tephra ring extend from 1000 mbsl to 650 mbsl, have basal diameters ranging from 5 km to 1 km and attain heights of up to 350m. The caldera walls are characterized by pillowed flows with distinct radial joints that are conformably overlain by thick, massive to graded deposits of coarse lapilli tuff to lapillistone that appear reasonably well size-sorted. Intercalated beds of finer, sandy (ash-rich) lapilli tuff and thin bedded tuff deposits separate sequences comprised of coarser, thicker deposits. Talus deposits consisting primarily of pillow lava blocks cover the base of the caldera wall and the immediate caldera floor. The caldera margin tephra deposits and cones are truncated by caldera margin faults and portions of the tephra deposits have collapsed into the caldera floor during caldera collapse.

Hydrothermal venting in the Monowai Caldera, south of the central cone was discovered by Embley et al. (2005) during the NZASRoF'05 expedition in 2005.

A 1 x 1.5 km, north-east elongate pillow volcano occupies the northwestern half of the caldera floor (Fig. 5.9). Northeast- and northwest-trending faults control the location and form of the pillow volcano and also segment the caldera floor. One such fault, a prominent northeast-southwest trending fault, defines the northern margin of the pillow volcano, extends up the caldera wall and the Mussel Ridge Hydrothermal field is located immediately south of this fault at a water depth of approximately 1200 mbsl. Pillow lava in the Mussel Ridge area is covered by less sediment than the caldera floor pillow volcano and may, therefore, be a product of a younger basalt eruption localized at the intersection between a caldera wall fault and the southwest-trending fault.

5.3.2 ROPOS Operations

When the cruise reached the first planed station point on Monowai volcano on 1 May, audible "bumping" of the ship and visible discoloration and upwelling at the surface was noted in several places, most likely related to steam explosions from the small cone building on the southern flank of the summit and along the length of the scar left from the 1998-2004 collapse (see below). This activity occurred along the length of the scar from 200 m water depth to at least 500 m depth.

ROPOS dive R1041 surveyed the collapsed summit of Monowai Seamount (Fig. 5.12). The ROV landed at about 3350 m depth and climbed up the debris slope toward the active cone. Visibility was significantly reduced owing to continuous turbidity currents shedding off the building cone. A large area along the southeast scar of the sector collapse was unapproachable due to continuous steam eruptions and turbidity currents. Bombs were observed locally in the debris fans coming off the building cone. Subsequent EM120 data showed that the erosional scar from the sector collapse between 1998and 2004 has been almost completely filled in. The dive was abandoned due to zero visibility as the active cone was approached.

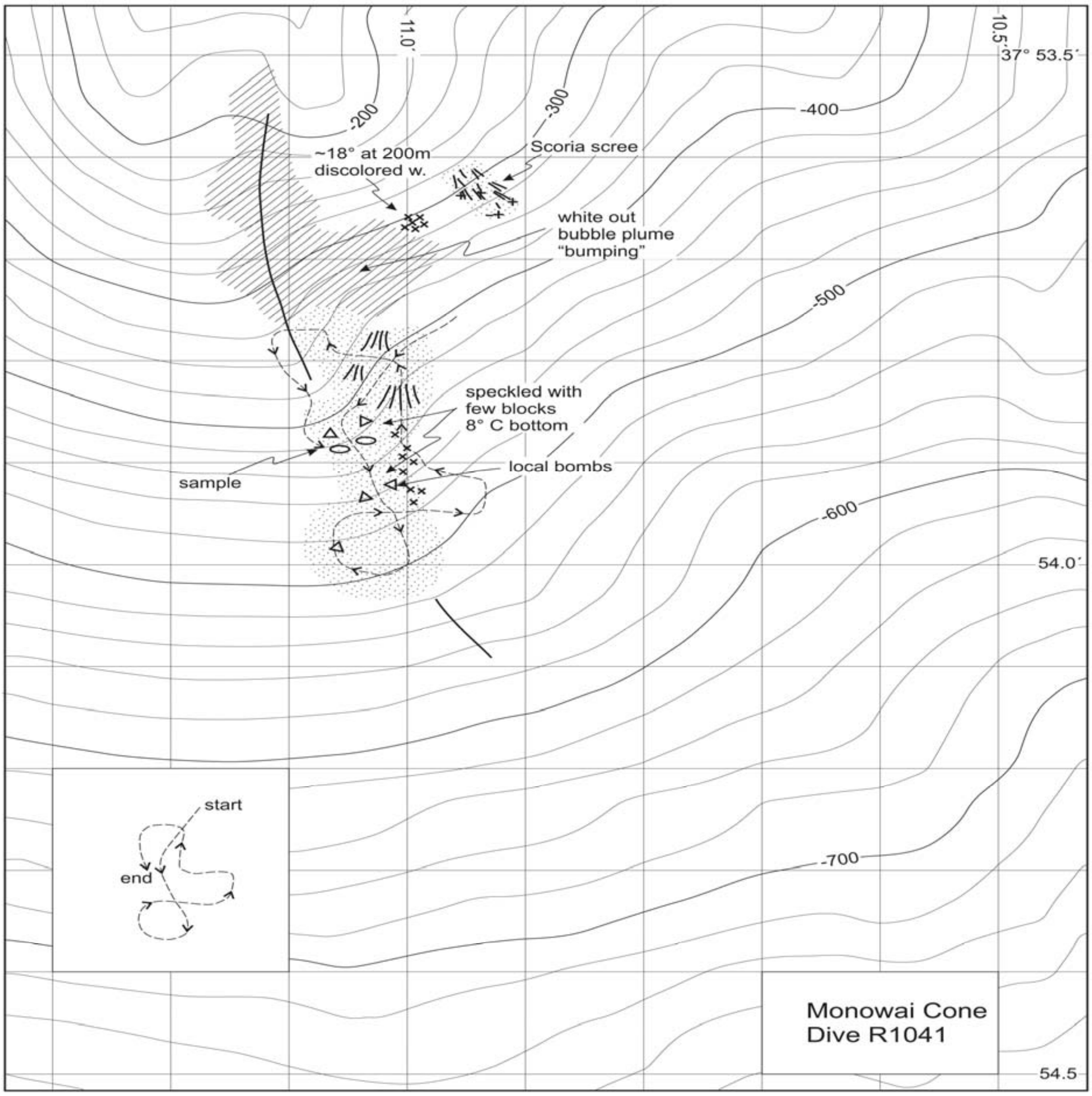


Fig. 5.12: Geological map of the collapsed summit of Monowai Seamount, dive R1041.

ROPOS dive R1042 surveyed the base of the original constructional edifice of the Monowai volcanic complex as exposed in the deepest part of the eastern caldera wall (Fig. 5.13). The base of the eastern wall exposes a stepped slope of massive basalt with visible pillows. Few outcrops were observed and much of the slope was covered by blocky talus of massive basalt from 1560 m depth to 1200 m depth. Ledges of pillow lavas and coherent flow material were also observed between 1200 and 1080 m with a flow top breccia at 1040 m to 1000 m depth. The upper part of the section from 1000 m to 800 m consisted of bedded volcaniclastic material covered by fresh scoria and black sand with possible sills of more massive coherent material. Further diving on the caldera walls was abandoned in favour of TV-grabs, as the walls of the caldera were found to be heavily sedimented, except at the very bottom of the caldera wall where massive coherent basalt units are exposed. It was not possible to observe the upper pyroclastic units.

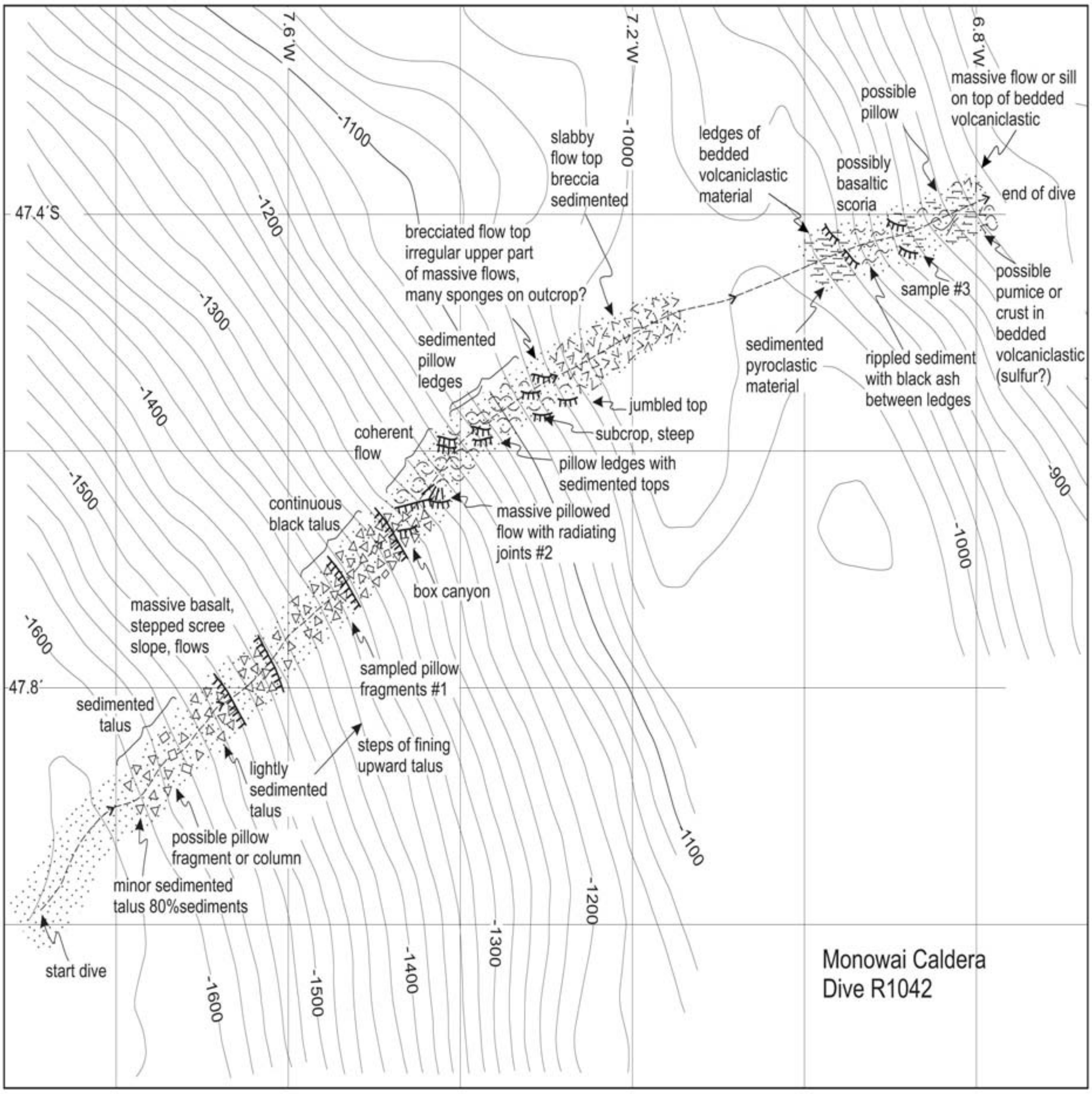


Fig. 5.13: Geological map of the deepest part of the eastern caldera wall of Monowai Caldera, dive R1042.

Dive R1043 was conducted at the vent site Mussel Ridge. ROPOS climbed from the drop point at 1530 mbsl at the bottom of the cone towards the south and southwest to Mussel Ridge (Fig. 5.14). Numerous areas of diffuse venting in this area were relocated at a depth of about 1152 m at this site (PISCES Marker 8). Vents at 15°, 24°, 30° and 39°s C were located and sampled. Dense coverage of mussels was mapped on the flank and along the northwest trending summit of Mussel Ridge. Several sulfur chimneys and tube worm clusters also were observed. The summit of Mussel Ridge consists of a linear outcrop of massive coherent basalt, possibly a dike swarm or linear pillow volcano. All outcrops were heavily encrusted by mussels.

ROPOS Dive R1044 focused on the sampling of vent fauna and vent fluids at Mussel Ridge (Fig. 5.15). Further diving on the caldera walls was limited by a heavy sediment cover.

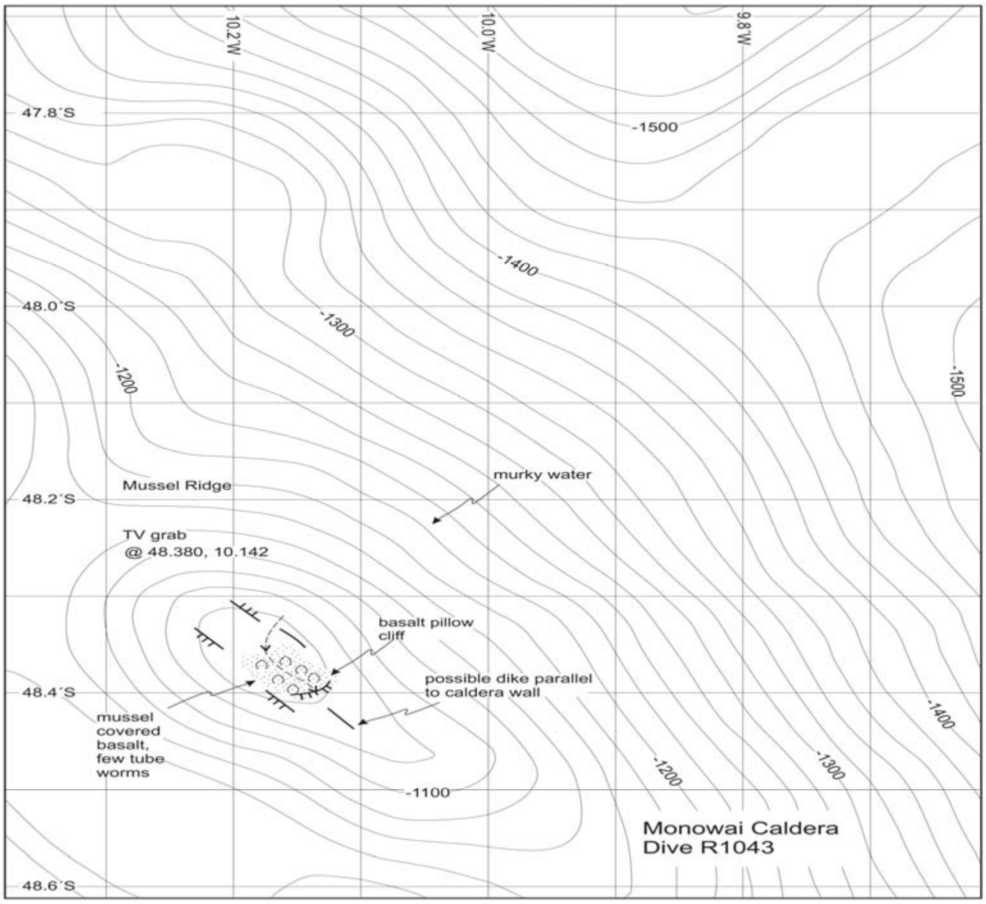


Fig. 5.14: Geological map of the vent site Mussel Ridge, Monowai Caldera, dive R1043.

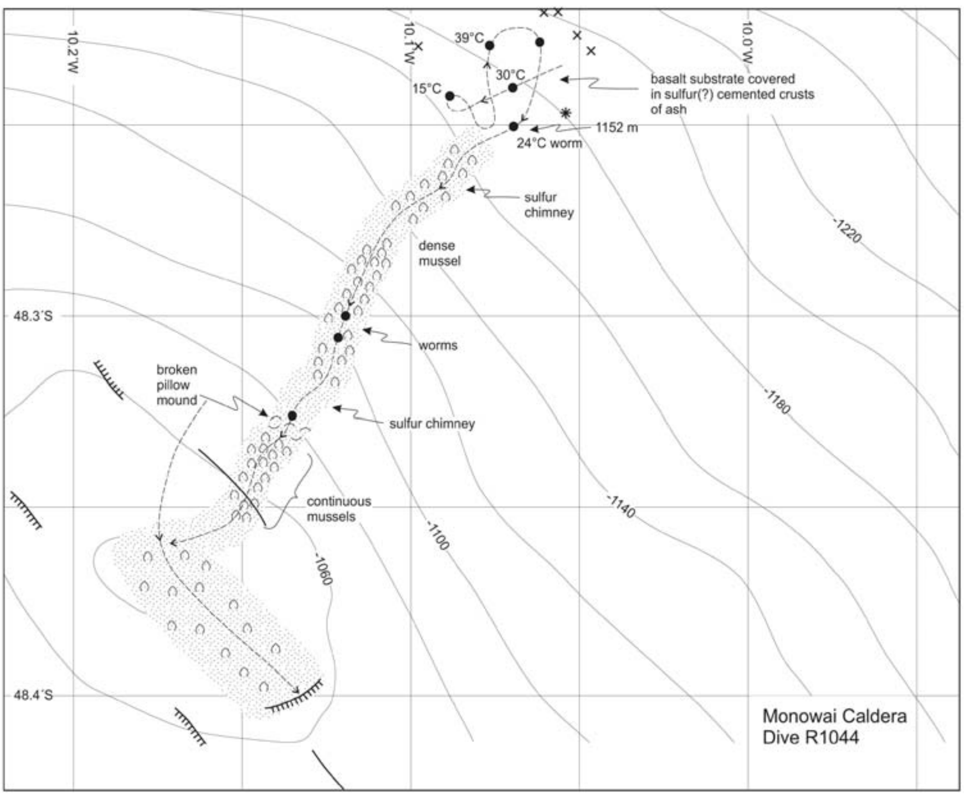


Fig. 5.15: Geological map of the vent site Mussel Ridge, Monowai Caldera, dive R1044.

5.3.3 Sampling

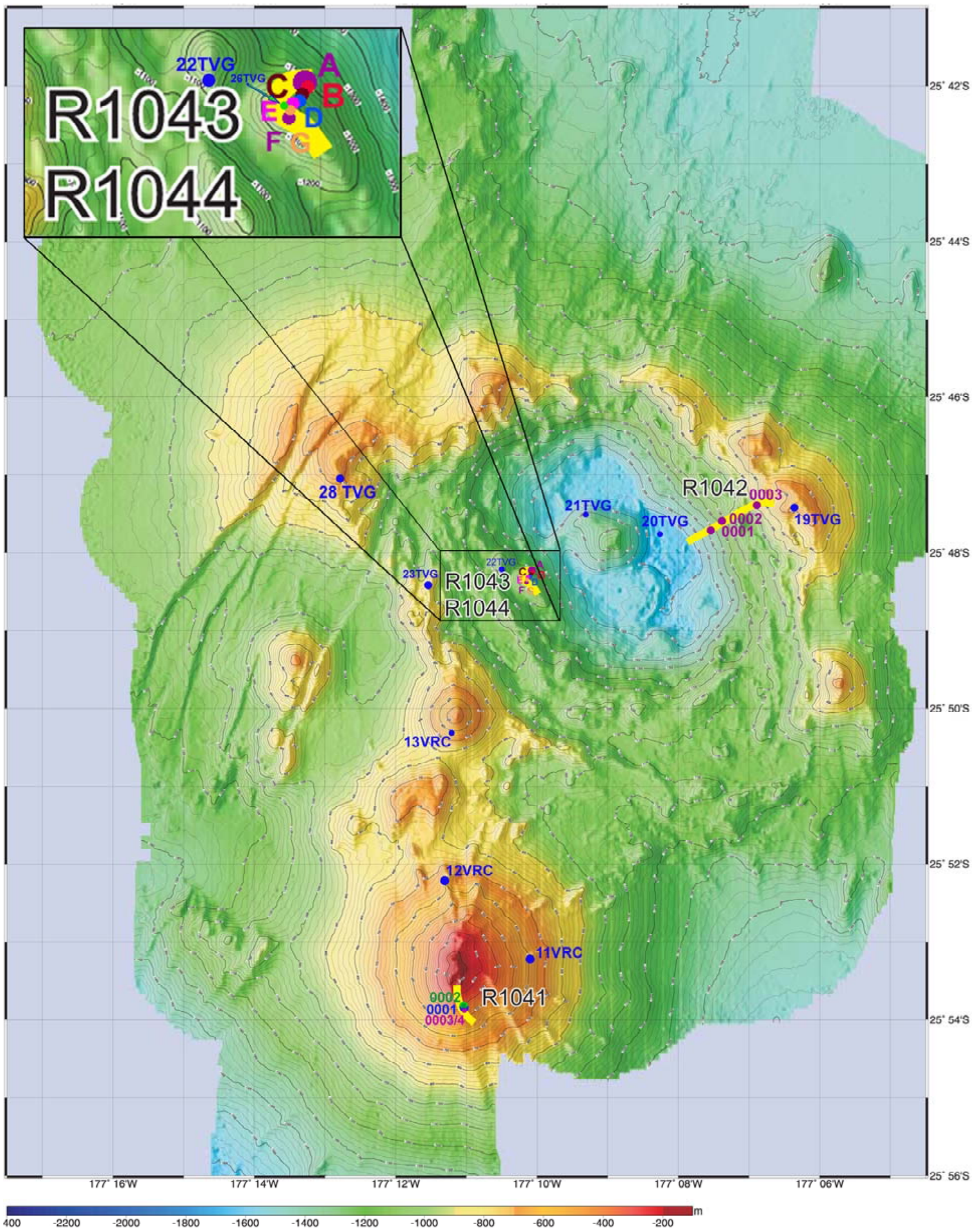
Monowai Volcanic Cone

The summit area of Monowai volcanic cone was sampled during ROPOS dive R1041 and by wax corer stations 11VRC and 12VRC (Fig. 5.16). Rock samples from the cone site are of basaltic composition und vary from aphanitic to porphyric with approximately 20% plagioclase phenocrysts up to 10 mm in diameter. Some of the samples are highly vesicular and show glassy rims. In addition to the known basaltic composition, SiO_2-rich scoria ash was discovered for the first time at the cone site. ROPOS suction samples from the water column recovered predominantly vesicular, glassy ash up to 2 cm, with crystals of sanidine, clinopyroxene, quartz, and plagioclase.

The small cone just south of Monowai caldera was sampled by wax corer station 13. Volcaniclastic fragments of plagioclase-phyric basalt up to 10 mm in diameter were sampled.

Monowai Caldera

The Monowai caldera was sampled during ROPOS dives R1042, R1043 and R1044, and by TV-grab stations 19TVG, 20TVG, 21TVG, 22TVG, 23TVG, 26TVG, 27TVG, and 28TVG (Figs. 5.16, 5.17). Volcanic rocks are represented by highly vesicular, aphyric, glassy basaltic lava and partly oxidized basaltic volcaniclastics. Alteration is weak and related to seafloor weathering. Samples from the resurgent dome in the center of the caldera are characterized by fresh aphyric, highly vesicular basaltic lava and few pillow fragments. The sampled material from the vent sites comprises barite-pyrite and sulphur-rich crusts and altered micro-vesicular basaltic lava. The partly advanced altered, aphanitic rocks show white coating (clay and possibly Al-Hydroxide) developed in fractures, which are also mineralized with pyrite, realgar and barite. Molten native amorphous sulfur occurs as disseminations and as centimetre-thick layers within lapilli material, in veinlets and in worm tubes.



Samples R1043:	**Samples R1044:**
A: 0001/2 = 27TVG	B: 0001-08
B: 0003/4	G: 0009-11
C: 0005	E: 0012
D: 0006-10	
E: 0011	
F: 0012	

Fig. 5.16: Bathymetry of Monowai Volcanic Complex (MVC), tracks of the ROPOS dives R1041 to R1044, and sampling locations.

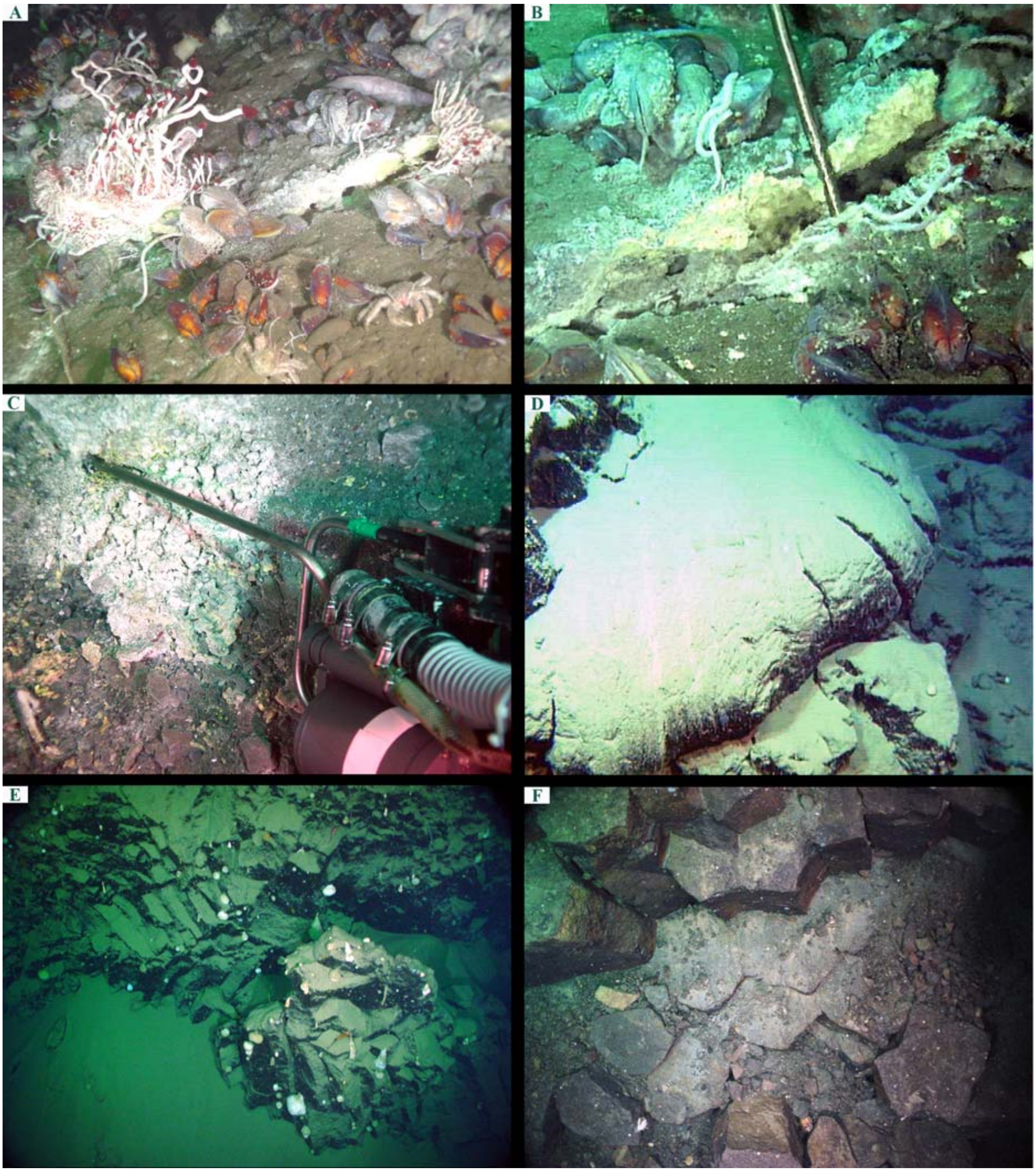


Fig. 5.17. Hydrothermal activity and volcanic outcrops of the Monowai Volcanic Complex, northern Kermedadec island arc, SW Pacific. A: Ventfauna, altered rocks and sulphur precipitations at the so-called „Bouquet vent“ of the Mussel Ridge site. B: Fluid sampling at a low-temperature discharge vent at Mussel Vent (fluid temperature: 24°C). The fluid discharges from a crack with precipitates of native sulphur. C: Sampling discharging fluids of 42°C at Pisces 8-site with shimmering water (upper left corner). The surrounding rocks are bleached, related to alteration by the hydrothermal fluid. Precipitations of native sulphur are associated with the immediate vicinity of the vent. D: Lobate basaltic lava flow in the vicinity of a massive intrusive dike close to Mussel Ridge. E, F: Columnar jointed basalts related to the intrusion of massive vertical dikes.

5.4 Volcano U (#21; 25°25.5 S, 177°05.8 W), Northern Kermadec Arc

5.4.1 Bathymetry and Structure

The arc volcano immediately north of Monowai Volcanic Complex at 25°25.5 S, 177°05.8 W is a very symmetrical, cone-like volcano. The volcano represents one of the northernmost volcanic seamounts in the Kermadec island arc. Tagudin and Scholl (1994) described a pair of volcanoes near 25°10'S according to seismic evidences. During SO-167, no volcanic structures were found, based on the given coordinates. Subsequent mapping by other cruises identified two volcanoes designated as Volcano U (#21) and V (#22), respectively. Bathymetry is based on these cruises (Fig. 5.18) and the survey during SO-192/2 aimed mainly at the volcanic stratigraphy of Volcano 21. It was surveyed during one two-hour dive that focused on examining part of the north-northeast wall of a funnel shaped, 2 x 2 km caldera. The Volcanic complex consists of a symmetric cone with shoals to water depth of 160 m. The caldera is characterized by volcanic ridges trending outward from the upper caldera wall close to the base, most prominent in the NW and the SE. The wall of the volcano is characterized in the NW and the SE by the occurrence of larger depressions, likely representing small scale crater pits. There are no obvious indications for recent volcanic or hydrothermal activity in the surveyed parts of the caldera.

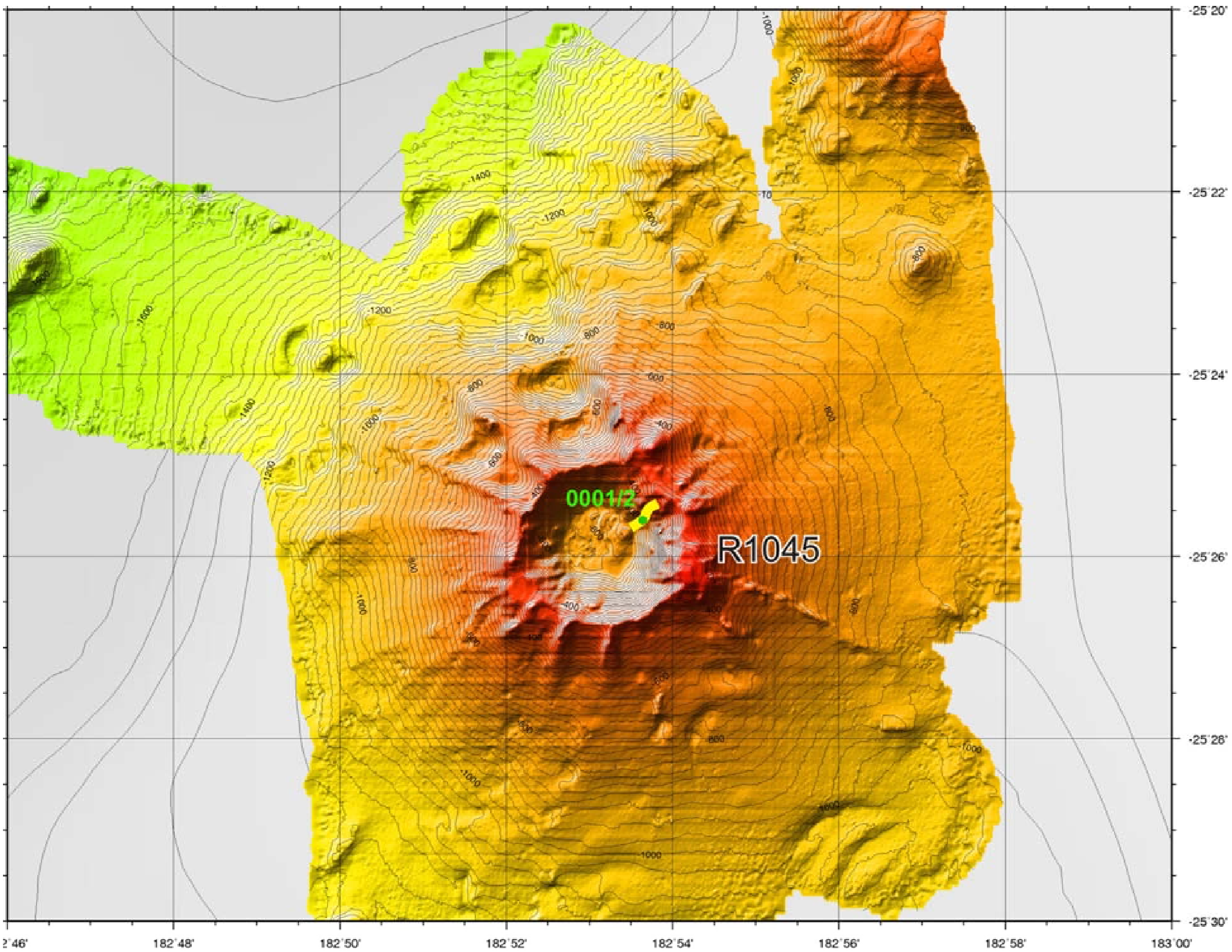


Fig. 5.18: Bathymetric map of Volcano U (#21), northern Kermadec arc. Dive track and sampling position of R1045 are given.

5.4.2 ROPOS Operations

ROPOS dive R1045 surveyed the summit caldera on the volcano. ROPOS was dropped in the northeast corner of the caldera at 650 m water depth and then surveyed towards the top of the caldera wall at 200 m water depth. The geology of the inner caldera wall is dominated by a swarm of dikes at the base at 670 m depth, which has a thickness of up to 300 m, with screens of weakly bedded coarse volcaniclastic material (Fig. 5.19). The dikes die out toward the top of the caldera wall. The uppermost part of the wall (above 365 m water depth) consists of unconsolidated ash and lapilli.

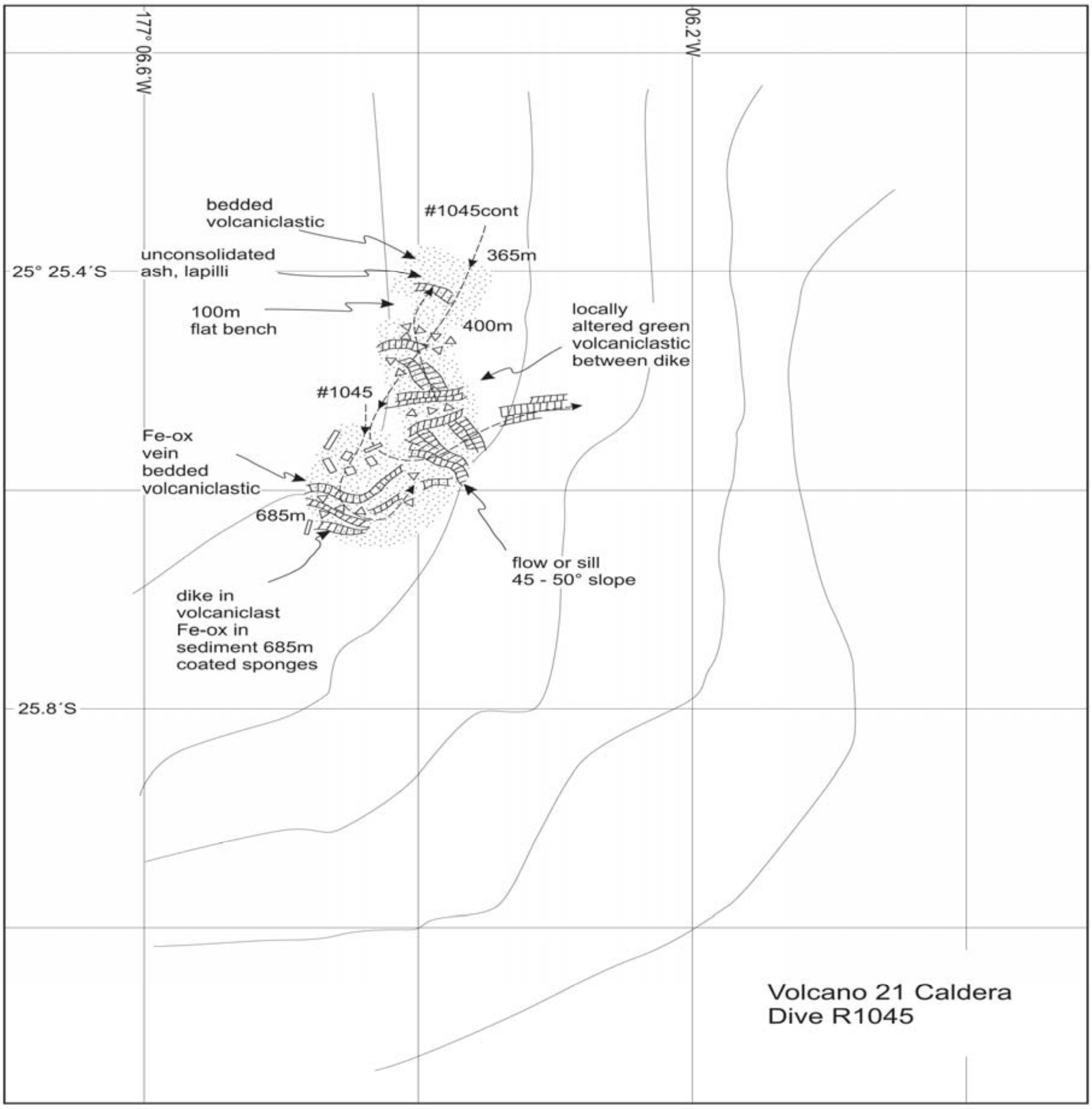


Fig. 5.19: Geological map of eastern caldera wall of Volcano U (#21), dive R1045.

Significant observations include:

1) The base of the vent/crater at about 670 mbsl is covered with coarse talus deposits containing blocks of aphyric and distinctly plagioclase porphyritic basalt-andesite. The blocks have a brown colouration on their surface and are covered by tube-like biota.

2) From about 660 mbsl to 550 mbsl, spectacular, columnar jointed basalt-andesite dikes dominate the wall. Between the dikes are thin screens (cm to meters thick) of brown coloured

volcaniclastic rocks containing dark grey angular clasts up to 15cm in size in a brown, finer-grained (altered) matrix. The volcaniclastics appear to be framework supported and massive (bedding not observed). Margins of the dikes are brown coloured as are joint surfaces within the dikes.
3) At about 550 mbsl, Fe-staining in the volcaniclastics and dikes decrease and at about 420 mbsl the volcaniclastics and some of the dikes have a green colour.
4) Bedding in the volcaniclastics was first noticed at 535 mbsl and it becomes more common at shallower depth. There is indication that it may dip inward towards the crater.
5) Overall the section from 670 to about 300 mbsl contains more than 75% dikes. Two columnar jointed sills were observed at 540 and 475 mbsl.
6) This crater appears to be a volcanic vent and the cone was likely constructed by pyroclastic eruptions from this central vent. The numerous basalt-andesite dikes suggest the vent is localized along a fissure, the orientation of which is unknown.

5.4.3 Sampling

The Volcano U was sampled during ROPOS dive R1045. Volcanic rocks are represented by dense plagioclase- and clinopyroxene-phyric, slightly vesicular lava. Local Fe-oxide staining is related to seafloor weathering.

5.5 Volcano 19 (24°48´S, 177°01´W), Southern Tonga Arc

5.5.1 Bathymetry and Structure

Volcano 19 is a large stratovolcano located in the southernmost part of the Tonga arc. It was first described by Stoffers et al. (2003) and surveyed again with the Pisces submersibles during the SITKAP cruise in 2005 (Stoffers et al., 2006a,b). Investigations of hydrothermal plumes are also described by Massoth et al. (2003b, 2007).

The volcano has a basal dimension of 14 x 12 km and rises from a water depth of 1400 m to 385 m (Fig. 5.20). It has smooth flanks that rise to a complex summit peaking at 450 mbsl (Figs. 5.21, 5.22). The summit is dominated by an old caldera, an infilling cone, and a younger western caldera, all elongated in a NW–SE direction. The old caldera is poorly preserved, 3.2 km long by 2.2 km wide, and outlines the summit region. Only its eastern wall remains, together with a few sections of the northern wall. This caldera is now largely filled by a large younger central cone complex with a basal diameter of 1.7 km and a height of 300 m. The highest point is the volcano summit at 450 mbsl. The upper part of this complex comprises numerous explosion craters and pits, relict scoria cones, and a prominent ridge constructed of 2–3-m-wide vertical dikes. More recently, a crater may have blasted away much of the western wall of the old caldera. The younger caldera, 1.9 km in diameter with 200–600-m-high inner walls, occurs on the west side of the volcano. PISCES dives along the caldera walls during the SITKAP cruise revealed massive lavas (flows and sills) with spectacular columnar jointing and abundant dikes that extend from the floor to near the caldera rim (180 m of vertical exposure). Lavas from Volcano 19 span a limited compositional range from basalt to basaltic andesite.

The cone complex has partly collapsed into this young caldera, and also down the outer southern flank of the volcano. Two small constructional edifices 250 m in diameter and <100 m-high occur on the caldera floor, indicated as resurgent cones or constructional dikes. At least 15 small cones, each <200 m across and <100 m-high, have broken through the smooth SW and NE flanks of the volcano. They form a SW–NE volcanic lineament that passes through the summit of Volcano 19 and a satellite cone 500 m-high with a basal diameter of 2.5 km further to the SW.

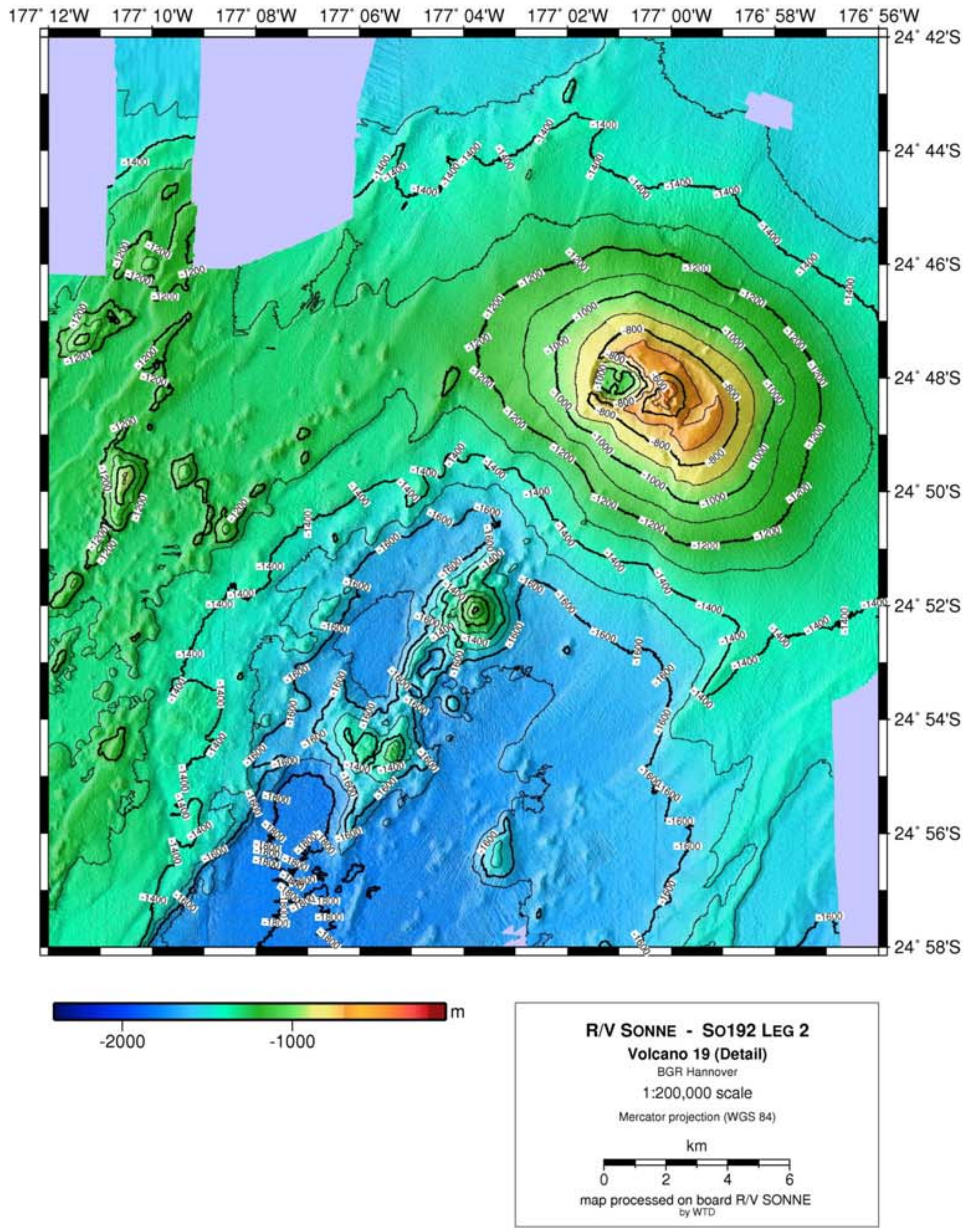


Fig. 5.20: Bathymetry of Volcano 19 and the western surroundings. The orientation of the regional structure follows the same NW-SE extensional pattern that affects the southern and northern Kermadec arc.

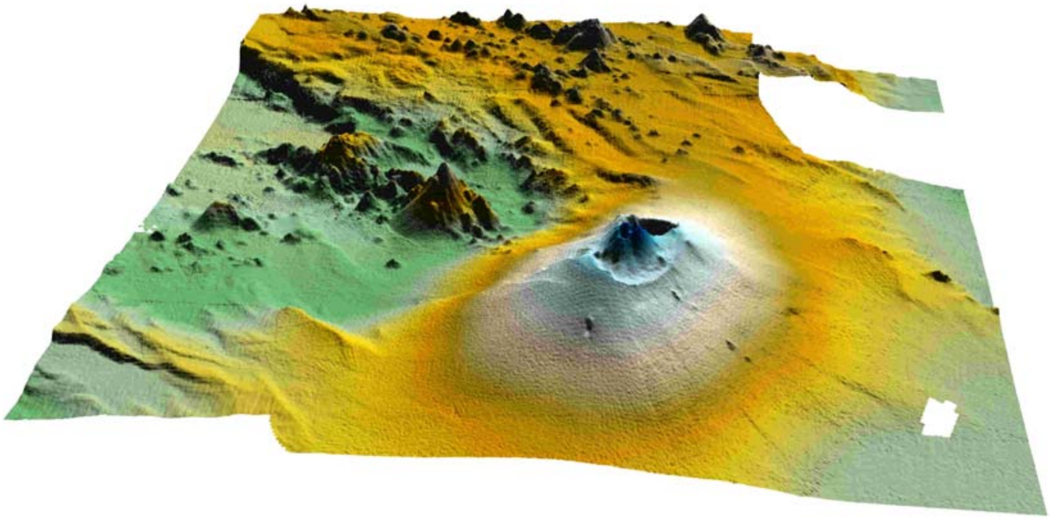


Fig. 5.21: 3-D bathymetric map of Volcano 19 and surrounding areas (view from N to S; refer to Fig. 5.20 for latitude and longitude position).

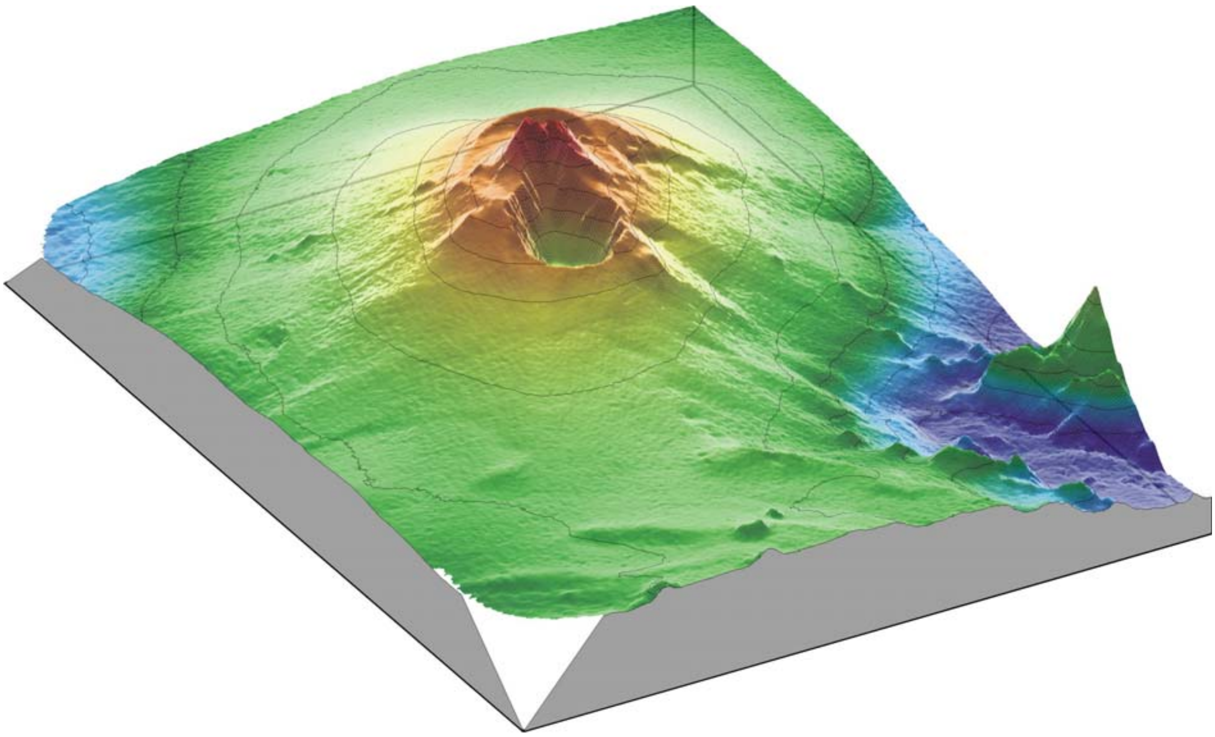


Fig. 5.22: Close-up 3-D bathymetric map of Volcano 19 (view from NW to SE; refer to Fig. 5.20 for latitude and longitude positions).

The regional structural pattern identified in the southern and northern Kermadec arc extends to the southern Tonga arc and reveals a prominent NW-SE extensional setting. The surroundings of Volcano 19 are characterized by a prominent volcanic ridge and the SW volcanic cone that extends to the SW from the arc volcano, and the young caldera, respectively. This ridge has developed within a larger basin or trough that outlines the same

NE-SW orientation. In contrast, the orientation of Volcano 19 displays a markable NW-SE trend perpendicular to the regional structural pattern. It seems obvious that this tectonic pattern extends for the entire volcanic arc. Volcano 19 adjoins a strongly tectonised ridge to the NW.

PISCES identified two large hydrothermal fields on Volcano 19. One is situated near the summit of the central cone between 385 and 540 m water depth. This is the biggest and hottest field which is known along the Tonga-Kermadec arc. The upper part of the central cone (an area of 800 x 800 m) is almost completely covered by Fe-oxyhydroxide crusts, formed from diffusely venting low temperature fluids. Chimneys composed of Fe-oxyhydroxides have formed where the venting fluids reach temperatures of 70°C. More focused, high temperature venting occurs along the narrow, NE-SW–trending ridge at the top of the cone complex. Here, clusters of large barite and anhydrite chimneys occur along a series of vertical dikes and faults. At slightly greater water depths (420–435 m) at the southern end of the ridge, large high-temperature chimneys show vigorous flow. Focused high-temperature venting also occurs at a water depth of 540 m in one of the shallow pit craters on the central cone. Here, small chimneys and low-relief mounds of barite and anhydrite protrude from the sediment in the pit. Clear two-phase venting occurs from the orifices of several chimneys. In 2005, the temperatures of venting fluids from Volcano 19 were directly on the boiling curve at their respective depths. This was consistent with the abundant visual evidence of phase separation.

A second, large area of low-temperature venting occurs among a swarm of dikes in the south wall of the western caldera. Here, Fe-oxyhydroxide crusts extend for more than 900 m along the base of the caldera wall and over a depth range of 985–850 m. Diffuse venting of warm fluids and mats of Fe-stained filamentous bacteria occur throughout this field. At the center of the field, large clusters of Fe-oxyhydroxide and silica chimneys cover an area of 200 x 300 m.

5.5.2 ROPOS Operations

Volcano 19 was surveyed by ROPOS dives R1046, R1047 and R1048 (Figs. 5.23, 5.24, 5.25). Dive R1046 surveyed the southern rim of the western caldera on the volcano (Fig. 5.23). ROPOS was dropped at the base of the southern wall. The first part of R1046 surveyed the known field of Fe-oxide chimneys and low-temperature vents along the base of the south wall of the Western Caldera. The 112° C vent (measured in 2005) was located in the center of the Fe-oxide chimney field. Shimmering water is venting from cracks within hydrothermal barite crusts. Silica-barite chimneys were observed near this highest temperature vent in the centre of the chimney field. Water, gas, and hydrothermal precipitates were sampled at this location, together with samples of bacterially precipitated Fe-oxides. Lower-temperature Fe-oxide chimneys were surveyed to the east of this location. Numerous chimney-like structures occur throughout the site. These edifices are concentrated in two areas; one is located near outcrops of basaltic dikes, the second field occurs some 500 m to the east (Fig. 5.24). The chimneys are always covered by microbial mats. Previous investigations have shown filamentous bacteria (similar to the iron-oxidizing genus Leptothrix) within the mat community. It seems obvious that the bacteria, at least in part, are responsible for the formation of these chimney-like structures. In the vicinity of the chimneys, the bottom is covered with Fe-oxyhydroxide crusts. The chimneys measure up to 2 to 3 m in height; they are extremely friable and composed of unconsolidated material. Temperature anomalies of up to 39.5°C were measured on top of the chimneys. The Fe-hydroxide material, agglutinated by microbial mats, forms characteristic cucumber shaped rolls, when it rolls down the hill. These structures are found in depressions all the way up to the top of the volcano.

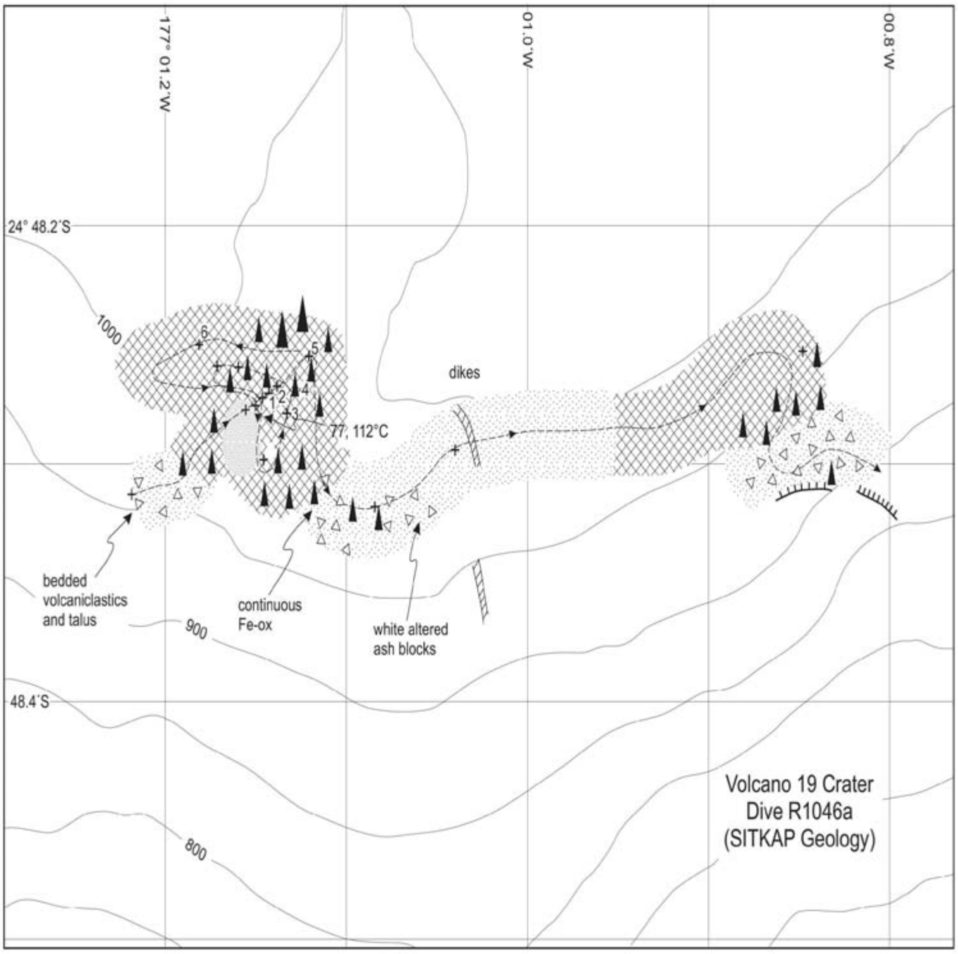


Fig. 5.23: Geological map of the southern wall of the young western caldera at Volcano 19, dive R1046a.

The second part of the dive studied the southern area of venting at the summit cone of Volcano 19. This part of the summit cone complex is covered by a large area of hydrothermally cemented ash with fractures lined by clays (nontronite?). A site for the study of the flat fish *Symphurus* spp was located among sulphur-cemented ash at the southern edge of this field.

Dive R1047 focused on the summit cone complex and the high temperature vents (Fig. 5.26). Fish traps were deployed at the southern end of the summit cone complex, and a survey was conducted in the area of a large clam field in a depression on the southwest flank of the summit complex. In water depths between 430 and 540 m mounds of chimney talus and active chimneys, associated with phase-separated fluid vents, were identified and sampled. A small vent with shimmering water of 36°C and associated Fe-hydroxide formation was sampled, and sulfur-cemented ash was observed at the southern edge of this field. In the same area vents of phase separated fluids of 270°C steam out of barite- and sulphide-rich chimneys and were sampled from the base of a broken chimney. This "flame-like" discharge caused by phase separation was already observed in 2005. The discharge is produced by a small jet of steam (H_2O vapor) that condenses rapidly in contact with cold seawater a few centimeters above the vent orifice.

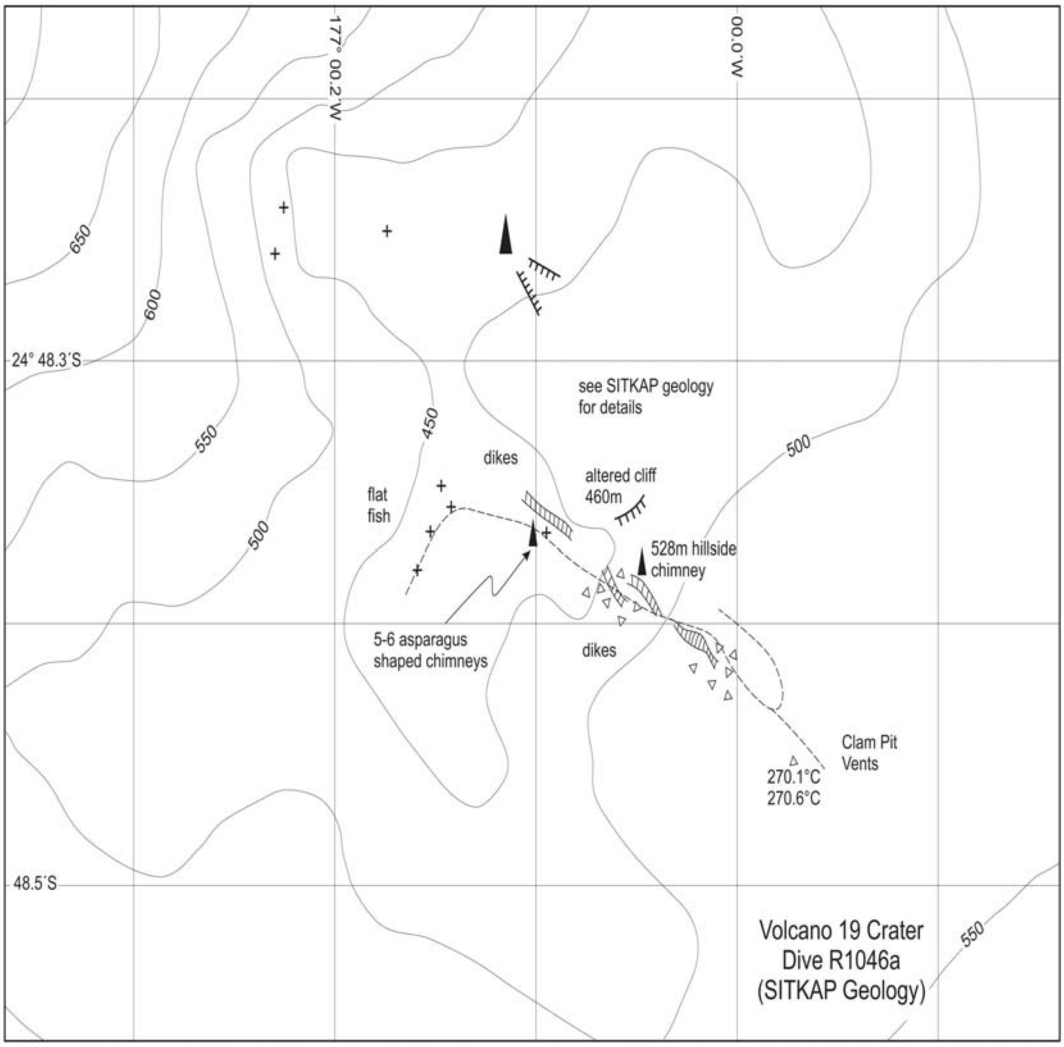


Fig. 5.24: Bathymetric map of the southern area at the summit cone of Volcano 19, dive R1046b.

Rapid growth of the edifices was demonstrated by a chimney with a growth rate of 24 cm per day. The process of phase separation at temperatures along the boiling curve for seawater promotes the formation of massive sulphides. Fluids were also sampled from a large barite chimney ("Big Fella") at the summit of the cone complex. This chimney was also identified during the SITKAP cruise and represents the biggest chimney edifice of the vent field.

ROPOS dive R1048 concentrated on the summit cone complex (Fig. 5.26). This dive was devoted to the sampling of biological specimens and water at high-temperature vents. ROPOS was deployed close to the large barite chimney ("Big Fella") where a detailed biological survey was carried out at the base of the edifice. The edifice has a height of ~15 m and carries a prominent beehive structure on its top (385 m mbsl).

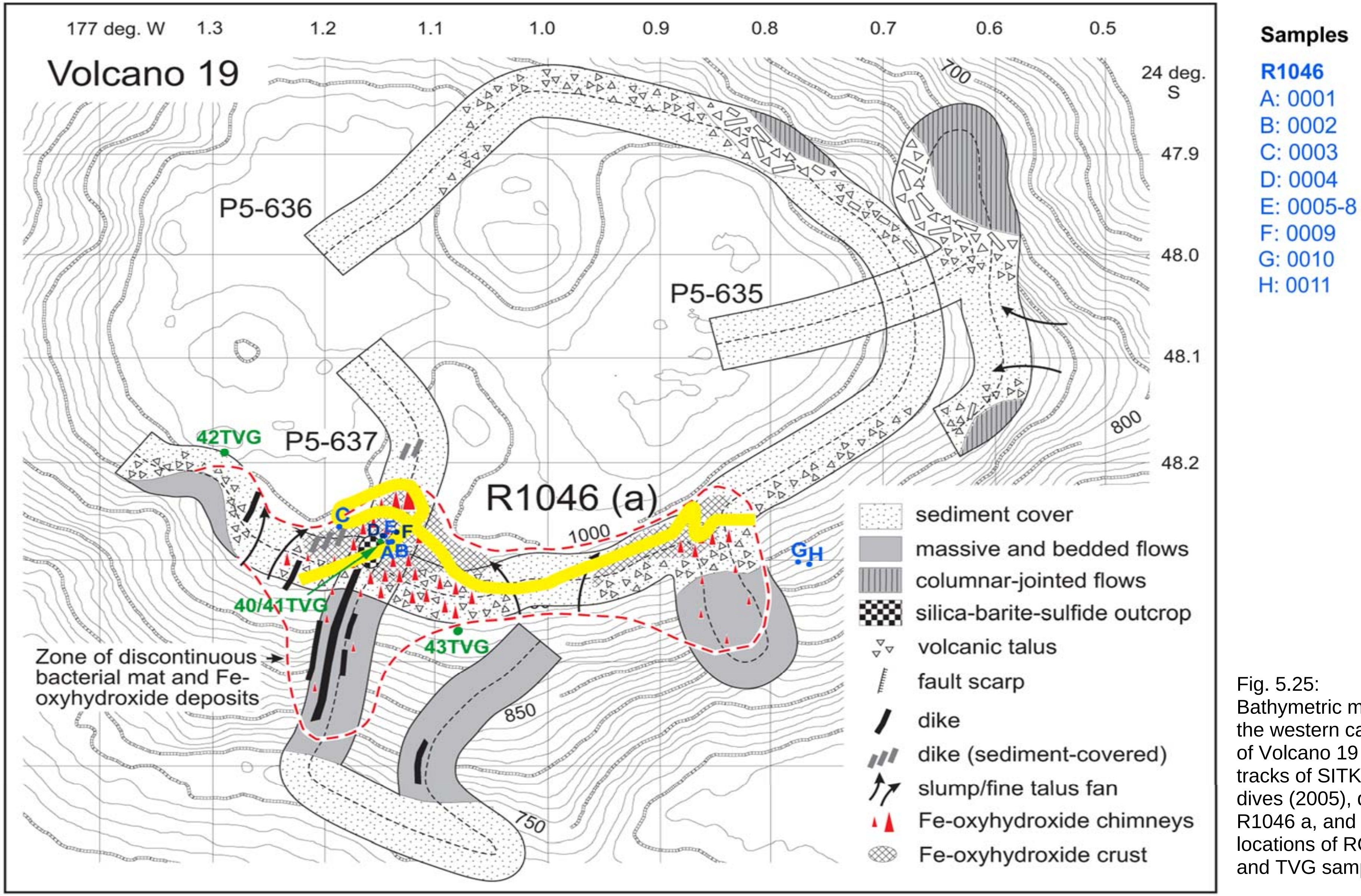
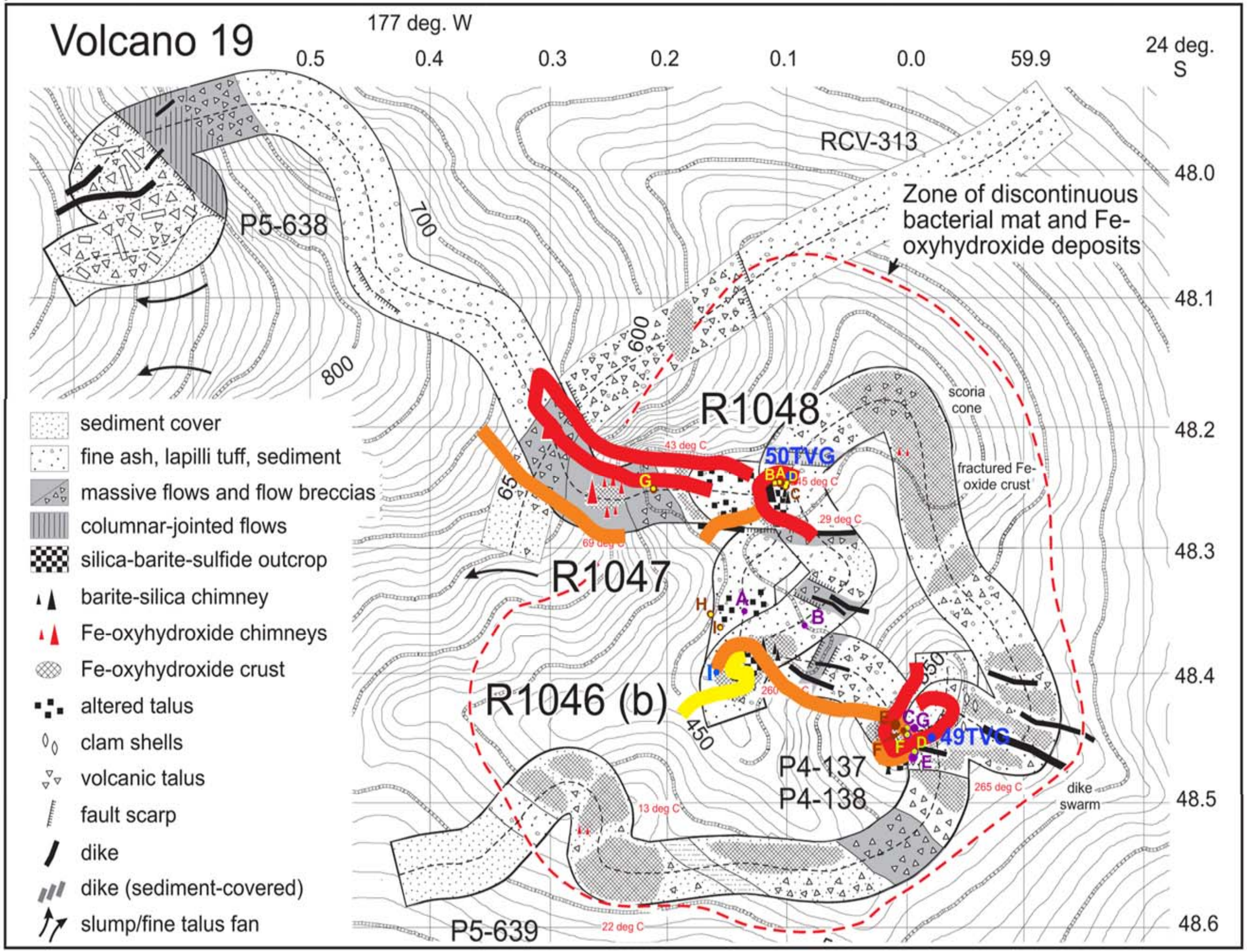


Fig. 5.25: Bathymetric map of the western caldera of Volcano 19 with tracks of SITKAP dives (2005), dive R1046 a, and with locations of ROPOS and TVG samples.



Samples

R1046
I: 0012/13

R1047
A: 0001
B: 0002-6
C: 0007-9
D: 0010
E: 0011-13
F: 0014
G: 0015

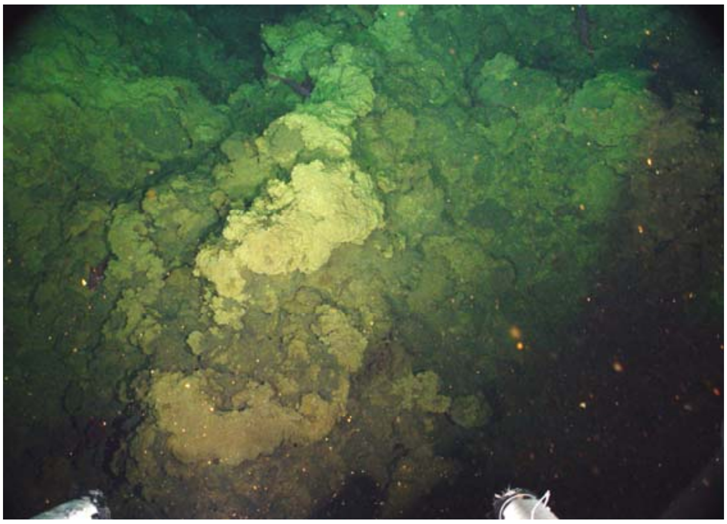
R1048
A: 0001-4
0006
0008
00010/11
B: 0005
C: 0007
D: 0009
E: 0012
F: 0013/14
E: 0015
G: 0016
H: 0017
I: 0018/19

Fig. 5.26: Cone area of Volcano 19 with tracks of SITKAP dives (2005), dive R1046b, R1047, R1048 and with locations of ROPOS and TVG samples.

The highest vent temperatures measured were 247°C. High temperature venting was also observed near the centre of the summit cone site. High-temperature fluids were sampled at chimneys near as well as from the top of "Big Fella". Chimney samples were collected from a silica-sulfate chimney close to the barite chimney. They consist mainly of barite, sphalerite/wurtzite and galena, together with rims of As-sulphides. On the western slope of the summit another field of small Fe-hydroxide chimneys was identified (Fig. 5.27). The fish traps were recovered and samples of bacterially precipitated Fe-oxides were taken from the Fe-oxide chimneys at the western flank of the cone complex.

Further diving at Volcano 19 was abandoned due to an approaching pressure low and operations were moved to the North.

Fig 5.27: Iron oxide precipitations on the western flank of the central cone.



5.5.3 Sampling

Volcano 19 was sampled during ROPOS dives R1046, R1047, R1048, and by TV-grab stations 40TVG, 41TVG, 42TVG, 43TVG, 49TVG, and 50TVG. Sampling targets are shown in Figures 5.28, 5.29, 5.30. Samples include volcaniclastic material, weakly consolidated volcanic ash, vesicular basaltic volcanic bomb with glassy crust, massive basaltic, slightly vesicular and plagioclase-phyric blocks of exposed dikes, highly vesicular and phyric pillow fragments, black aphyric glassy lava, and vesicular lava from the SW caldera wall. Alteration along the SW caldera wall is generally weak. It consists dominantly of clay alteration and Fe-oxyhydroxide staining. In the area of Fe-oxihydroxide chimneys, highly altered volcaniclastic material is indurated by sulphide (different generations of pyrite) and sulfate (barite) precipitates, clay minerals and amorphous silica. Locally worm tubes act as conduits for the discharge of warm hydrothermal fluids and are precipitated by the same assemblage. Samples from the central cone consist of sulphide and Fe-oxyhydroxide chimney fragments. The sulphide-sulfate chimneys are dominated by anhydrite, barite, sphalerite/wurtzite, pyrite, and galena. The outer zone of individual chimneys shows a ring of yellowish material, identified as an assemblage of As-sulphides and barite. A couple of sampled chimneys consist mainly of sulfates that are anhydrite-barite intergrowths. The cone also exists of intermediate to highly altered volcaniclastic material indurated by layers and patches of barite and anhydrite, and with minor fine-grained sphalerite/wurtzite, galena, pyrite. Fe- and Mn-oxide staining occurs on the surface. Most volcanic fragments are strongly altered and carry fine-grained pyrite, barite, and Fe- and Mn-oxide staining. Some samples, however, have a largely unaltered center.

In addition to rock sampling, six liquid and nine gas samples were recovered with ROPOS from the different vents in the caldera and on the cone with temperatures between 32 and

270°C. A single CTD station was deployed to investigate the vertical diffusion of the hydrothermal fluids and their mixing with seawater as well as oxidation processes of gaseous hydrocarbons in the water column.

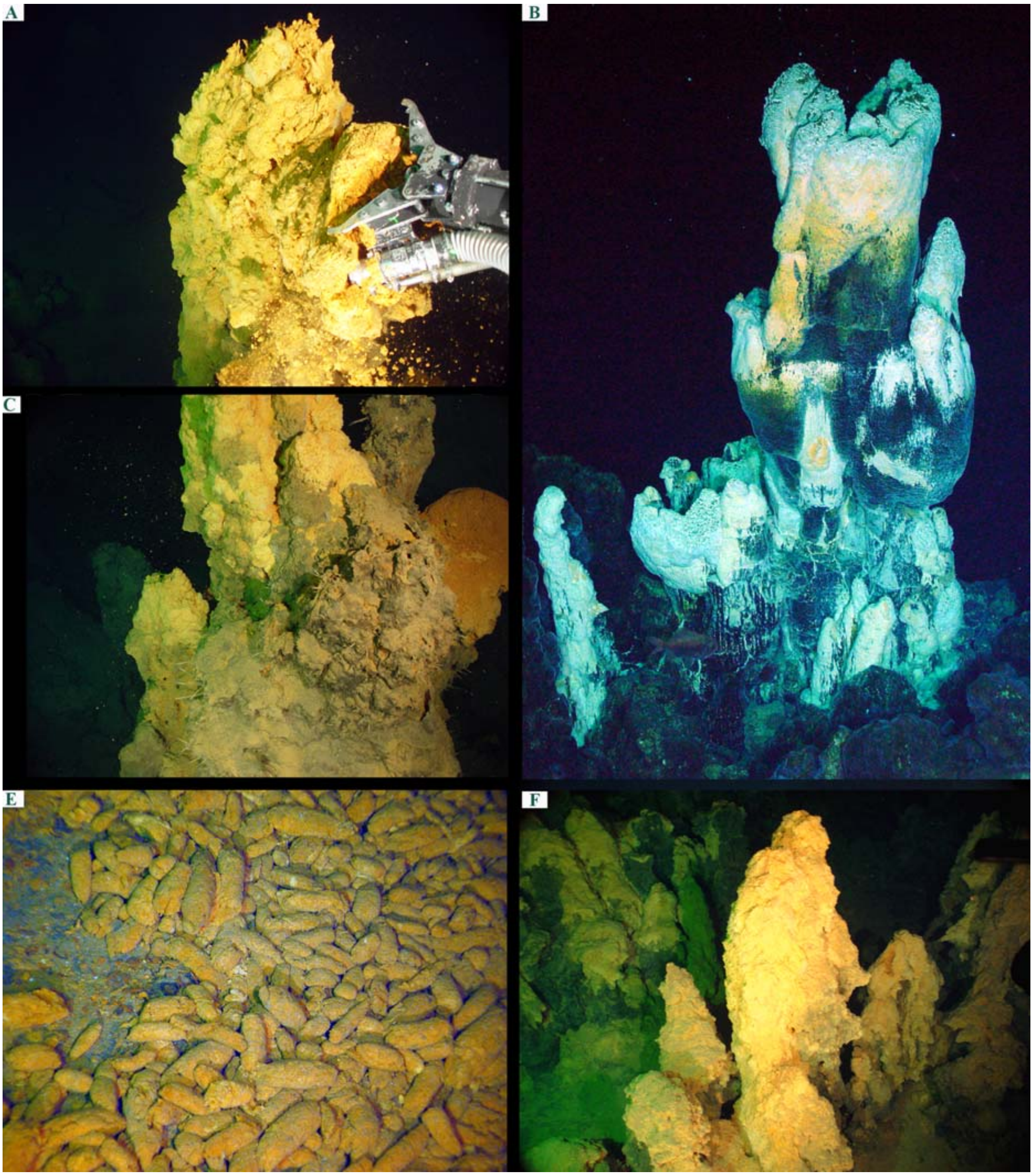


Fig. 5.28: Vent chimney edifices at Volcano 19. A: Sampling the top of a chimney consisting mainly of Fe-oxihydroxide in the caldera. B: Sulphate-silica chimney at the central cone complex with As-sulphides and Mn-oxides (yellow and black patches) at the outer wall. C, E: Fe-oxihydroxide chimneys as precipitates from low-temperature (~40°C) venting on the floor of the western caldera of the volcano. F: Iron oxide rolls, formed from eroded fluffy Fe-oxyhydroxide chimney tops, collected in depressions.

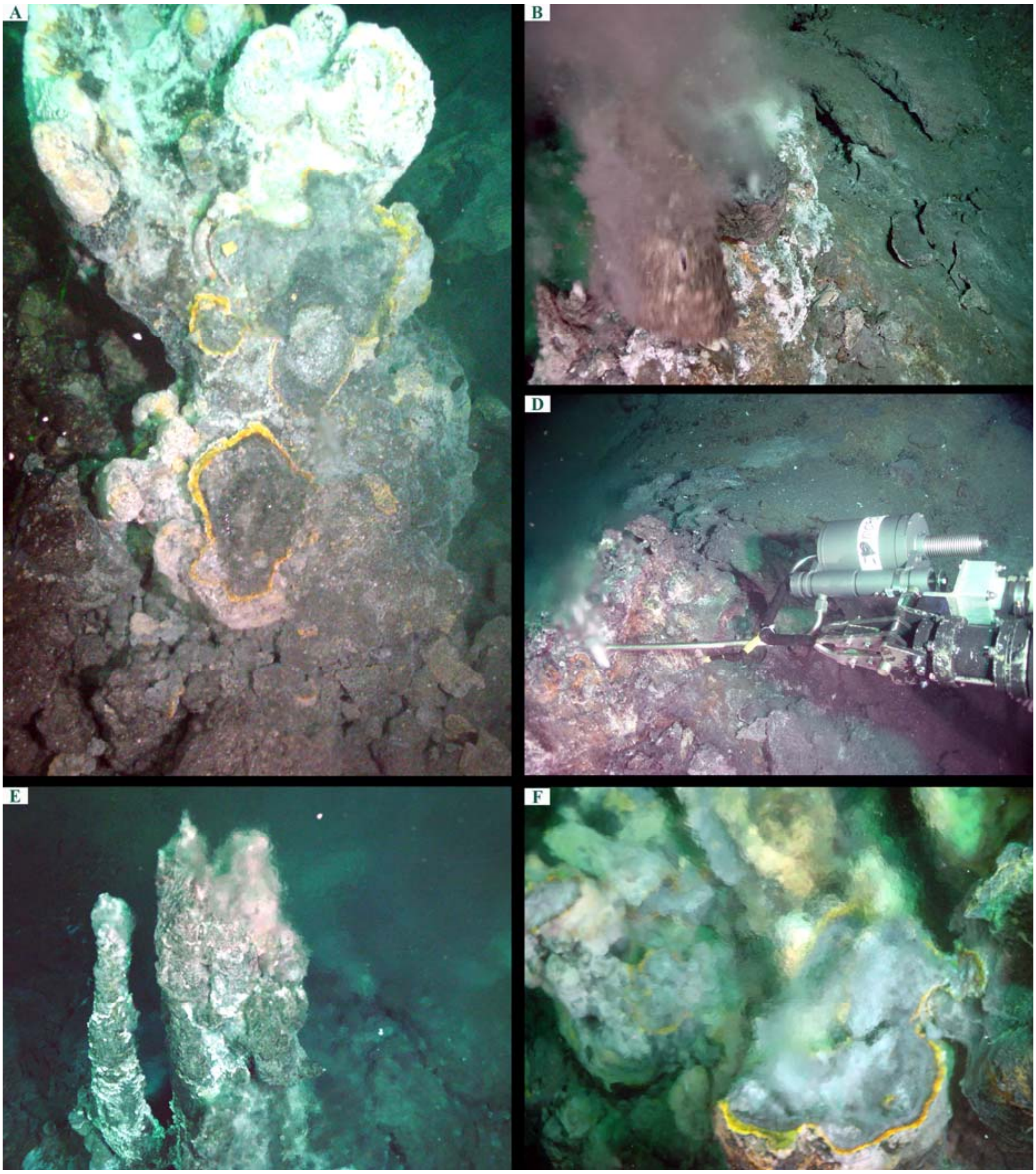


Fig. 5.29: Sulfate-sulphide chimneys of the central cone complex of Volcano 19. A: Sulphate-silica chimney with outer rims of yellowish As-sulphides. Shimmering water is discharging from multiple diffuse vents. B: Discharging vent fluids with black smoke from precipitating sulphides at the base of a chimney. D: Fluid sampling of phase separated fluids (note white flame-like stream of gas) at temperatures of 270°C. E: Sulphate-sulphide chimney edifices with shimmering water. F: Shimmering water of 242° C rising from the base of a knocked sulphate-ssulphide chimney. The central part of the chimney consists of sphalerite/wurtzite, the massive chimney wall is mainly barite-anhydrite, and the outer rim is characterized by a clear yellowish zone of As-sulphides.

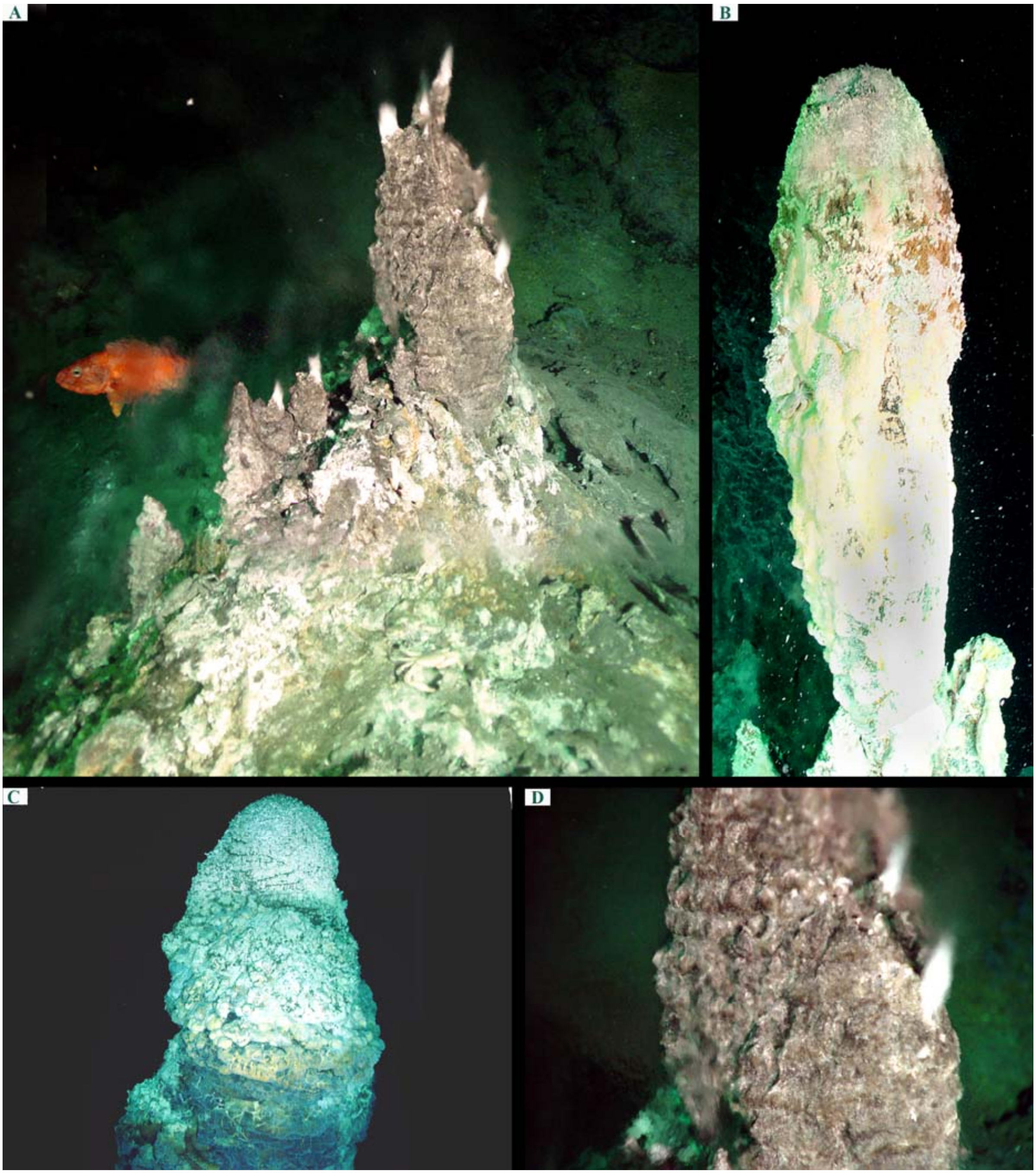


Fig. 5.30: Chimney edifices at the central cone of Volcano 19. A, D: Boiling process and discharge of two-phase fluids from multiple orifices of a fast growing chimney. The gas „flames“ are an impressive evidence for phase separation and subcritical boiling processes of the hydrothermal fluids, at a temperature 270°C in a water depth of 542 m. B: Sulphate chimney at the summit of volcano 19, based at 385 mbsl. C: Top of an approximately 15 m-high sulphate chimney with beehive texture on its very top. This edifice was named “Big Fella” and represents the tallest chimney in the high-temperature vent field of volcano 19.

A total of 268 organisms were sampled including several unidentified clams and a lucinid. Numerous Sclerasterias spp sea stars and unidentified vent crab species were also sampled. A total of five thalassinid reptants and a lithodid crab were sampled by the TV-grabs. One baited fish trap was deployed for the flat fish Symphurus spp but had captured on retrieval three sea stars only.

5.6 Hine Hina, (22°32´S, 176°43´W), Southern Lau Basin

5.6.1 Bathymetry and Structure

The extensional back-arc and southwards propagating Lau Basin opened by the successive southward propagation of discrete seafloor spreading centers. The site of active rifting is located at its southern end, the southernmost Eastern Lau Spreading Center (ELSC), commonly referred to as the Valu Fa Ridge. The Valu Fa Ridge was identified as a site of intense tectonic, magmatic, and hydrothermal activity which also makes it a type example for rift-related volcanism and associated hydrothermal processes. The Lau Basin, and its southern part, represents an environment which is commonly compared to ancient volcanic belts with respect to petrogenetic and metallogenetic processes. Evidence for active extension in the Lau Basin is provided by the shallow seafloor morphology, general thin sediment cover, the presence of magma chamber(s), the eruption of young tholeiitic basalts to rhyolites, geodetic and geophysical surveys, and vigorous hydrothermal systems (e.g., von Stackelberg and von Rad, 1990; Collier and Sinha, 1992; Fouquet et al., 1993; Hawkins, 1995ab; Taylor et al., 1996, Fretzdorff et al., 2006).

Valu Fa Ridge (VFR)

The southward propagating ridge extends for at least 165 km to 22°45' S, subparallel to the Tonga Ridge. It is 5 to 6 kilometers wide and generally strikes N20°E (Fig. 5.31). The ridge has a smooth crestal area that lacks a central axial graben structure, reaching a minimum depth of approximately 1600 m. In general, the bathymetry deepens to the south. Analyses of seismic data indicate that the entire central VFR (CVFR) is underlain by a robust axial magma chamber (Morton and Sleep, 1985; Collier and Sinha, 1990; 1992ab; Collier and Singh, 1997; Wiedicke and Collier, 1993). The Lau Basin crust ranges in element and isotopic chemistry from MORB to arc compositions (Hawkins, 1995b), whereat the ELSC rocks show high variability and transitional arc – back-arc signatures (Fretzdorff et al., 2006).

Hine Hina Segment (22°32'S)

The Hine Hina hydrothermal field was first identified during the NAUTILAU cruise in 1989 (Fouquet et al., 1989). It is hosted by segment number 5 according to Wiedicke and Collier (1993), an intermediate segment of the approximately 20 km-long SVFR (Figs. 5.32, 5.33). The segment displays four major bathymetric highs. The shallowest water depths (up to 1800 m) occur at the two southernmost edifices. This area was surveyed in detail during the NAUTILAU cruise (Fouquet et al., 1989; 1990; 1991; 1993), the SO-167 Louisville cruise (Stoffers et al., 2003, Fretzdorff et al., 2006) and the TELVE cruise (Massoth et al., 2007).

In 1989, the Hine Hina field was characterized by widespread diffuse discharge with hydrothermal crusts and single occurrences of inactive chimneys. Low temperature massive sulphide fragments and sulphide crusts are characterized by contributions of magmatic volatiles during their formation at the volcanic stage of this vent field. During the SO-167 cruise in 2002, this ridge segment was in a stable and largely inactive tectonic, magmatic and hydrothermal stage. Continued tectonic extension can be deduced from the presence of small, ridge-parallel cracks, both open and sealed, and the occurrence of sealed and open cracks within hydrothermal crusts (Stoffers et al., 2003; Fretzdorff et al., 2006).

The hydrothermal field is located only 25 km west of the Tonga island arc and extends for approximately 1 km north–south and 350 m east–west along the top and western flank of the ridge segment (Fig. 5.32). The extinct sulphide chimneys mostly occur partially buried by black to grey coloured volcanic sand that accumulated on the Fe-Mn oxyhydroxide crust or on underlying lobate and tubular flows. Sulphide talus, hydrothermal sediments, as well as hydrothermal vent fauna and shimmering water were observed along a fault scarp in massive lava.

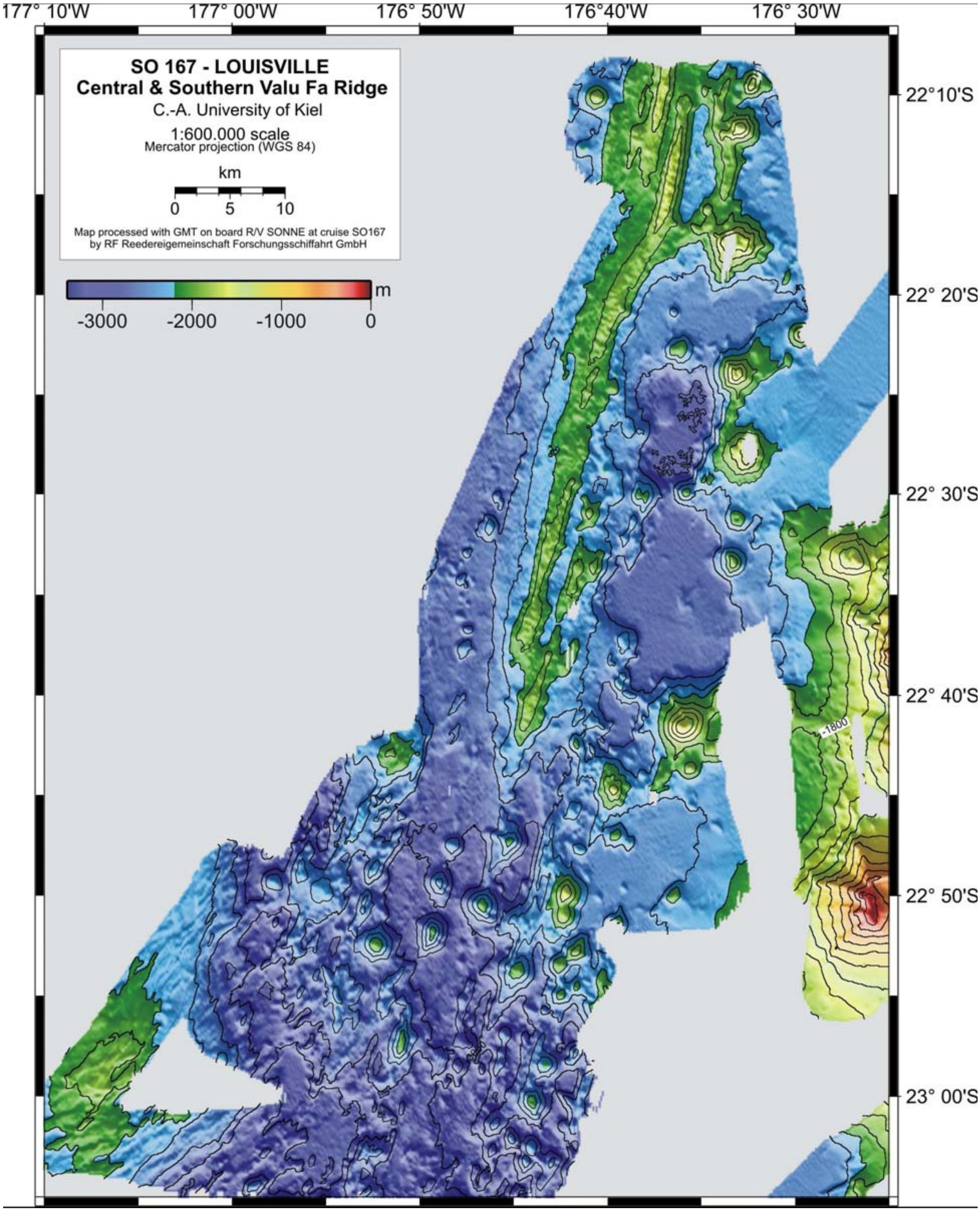


Fig. 5.31: Seafloor bathymetry of the central and southern Valu Fa Ridge, as recorded and processed by the multichannel SIMRAD EM 120 system during SO-167 (Stoffers et al., 2003; Fretzdorff et al., 2006) and the position of Hine Hina hydrothermal field at 22°32'S.

Fouquet et al. (1993) interpreted that the hydrothermal system was divided into two parts; a focused discharge along faults in massive lava, and diffuse discharge through the volcaniclastic pile in the upper part. Stoffers et al. (2003) described the extensive low-temperature hydrothermal discharge at the Hine Hina site as a product of a volcanic environment. Fretzdorff et al. (2006) assumed that passive fissure eruptions constructed pillow volcanic edifices along the Hine Hina ridge segment axis. The final stage of this construction was mild fire-fountain eruptions that blanketed the volcanic edifices with deposits of volcanic sand and bombs that were subsequently redeposited and concentrated by vigorous bottom currents to areas along their tops and flanks. Hydrothermal activity spanned the waning period of basaltic fissure eruptions and continued after fire-fountain eruptions as evidenced by altered and mineralized clasts in the volcanic sand, the occurrence of sulphide chimneys on lobate flows and within and buried by the black sand, and by the development of a Fe-Mn-oxyhydroxide crust on the black sand surface. The extensive crusts that cover much of the upper part of the edifice may be a product of unfocussed, diffuse low temperature hydrothermal discharge that was, in part, facilitated by the permeability of the porous volcanic sand upon which it developed. Evidence for recent hydrothermal activity includes a thermal anomaly in the immediately overlying water column, shimmering water and white–yellow biological mats. The Australian SS02/03 cruise (Arculus, 2003) found very weak hydrothermal plumes associated with the Hine Hina field.

Observations during the SO-192/2 cruise have largely confirmed the findings from the SO-167 cruise. There are no changes in the volcanic and the hydrothermal stage since 2002 and 1989 but continued tectonic extension can be deduced from the progression and slight widening of small, ridge-parallel cracks.

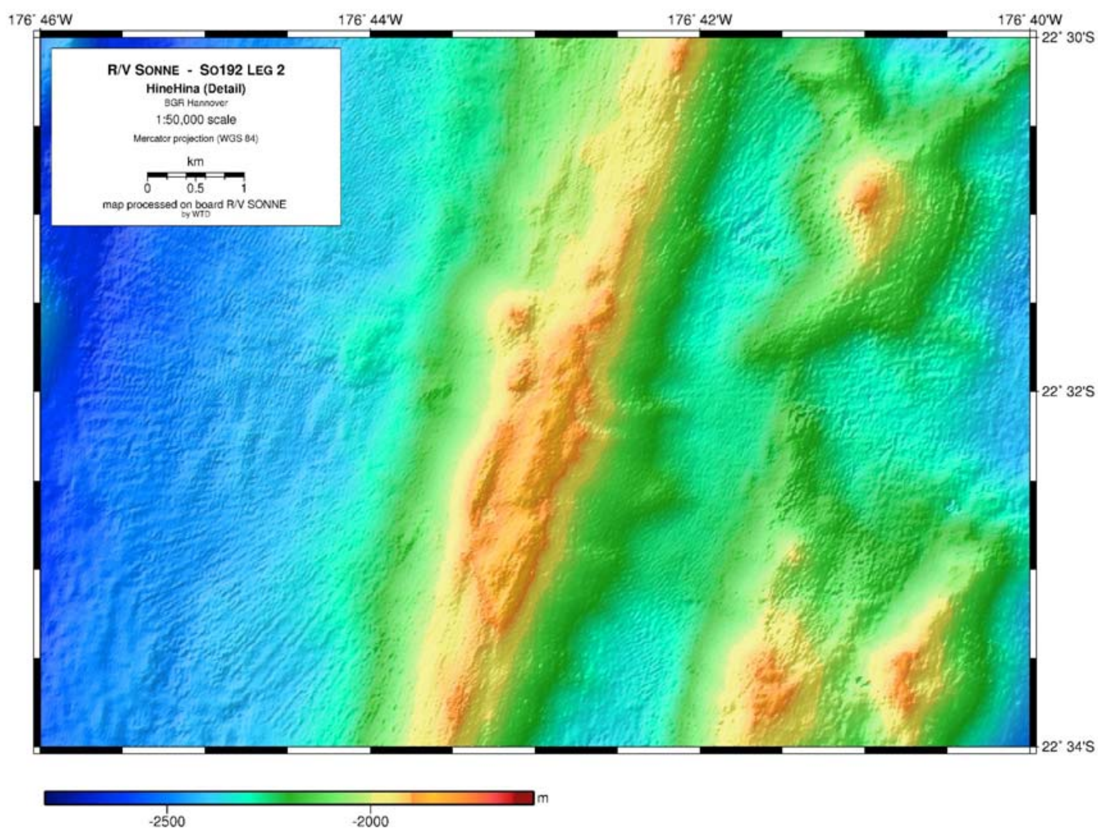


Fig. 5.32: Seafloor bathymetry in the area of the Hine Hina hydrothermal field at 22°32'S, southern Valu Fa Ridge.

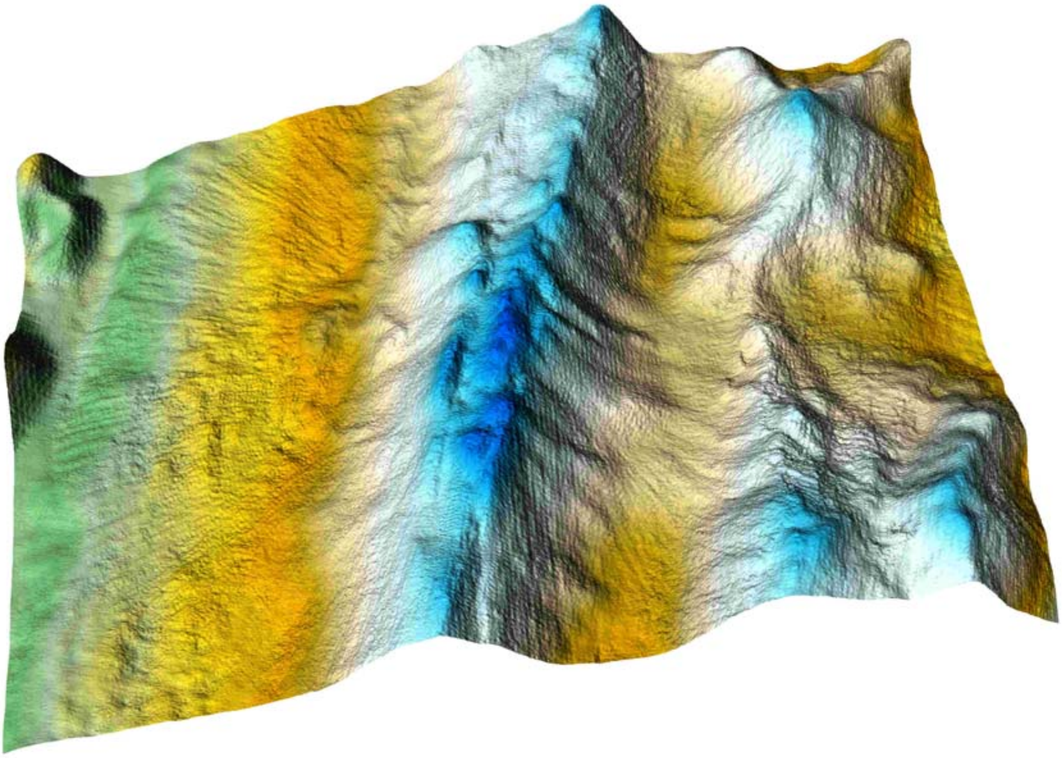


Fig. 5.33: 3-D bathymetric map of the Hine Hina segment and the area of the Hine Hina vent field in the center (view from S to N; refer to Figure 5.32 for latitude and longitude positions).

5.6.2 ROPOS Operations

The Hine Hina vent field was surveyed by ROPOS dive R1049 (Figs. 5.34, 5.35). The dive largely followed the SO-167 OFOS track and located the French NAUTILAU marker #98 in a field of mussels on a flank pillow cone adjacent to the main ridge segment. The recent hydrothermal activity is low temperature and diffusive, and outlined by patches of alive vent fauna (Bathymodiolus vent mussels, limpets, squat lobsters). Low temperature discharge causes the widespread formation of weakly consolidated iron- and manganese-hydroxide crusts. In certain areas, the crusts show distinct fractures and allow the more focused discharge of fluids and the fracture healing by the precipitation of Fe-oxyhydroxides. Pyrite and barite encrusted pinnacle-like edifices of hydrothermally altered (?) ash were located in areas where chimneys were reported. Only one area of relict chimneys was found in an area where NAUTILE had recovered stockwork mineralization. Along a fault scarp, massive sulphides and blocky fragments of inactive chimneys were sampled at this site by ROPOS and TV grab. The precipitates form massive Cu-rich mineralization. A survey of the mussel field on the adjacent pillow cone was conducted prior to the end of the dive.

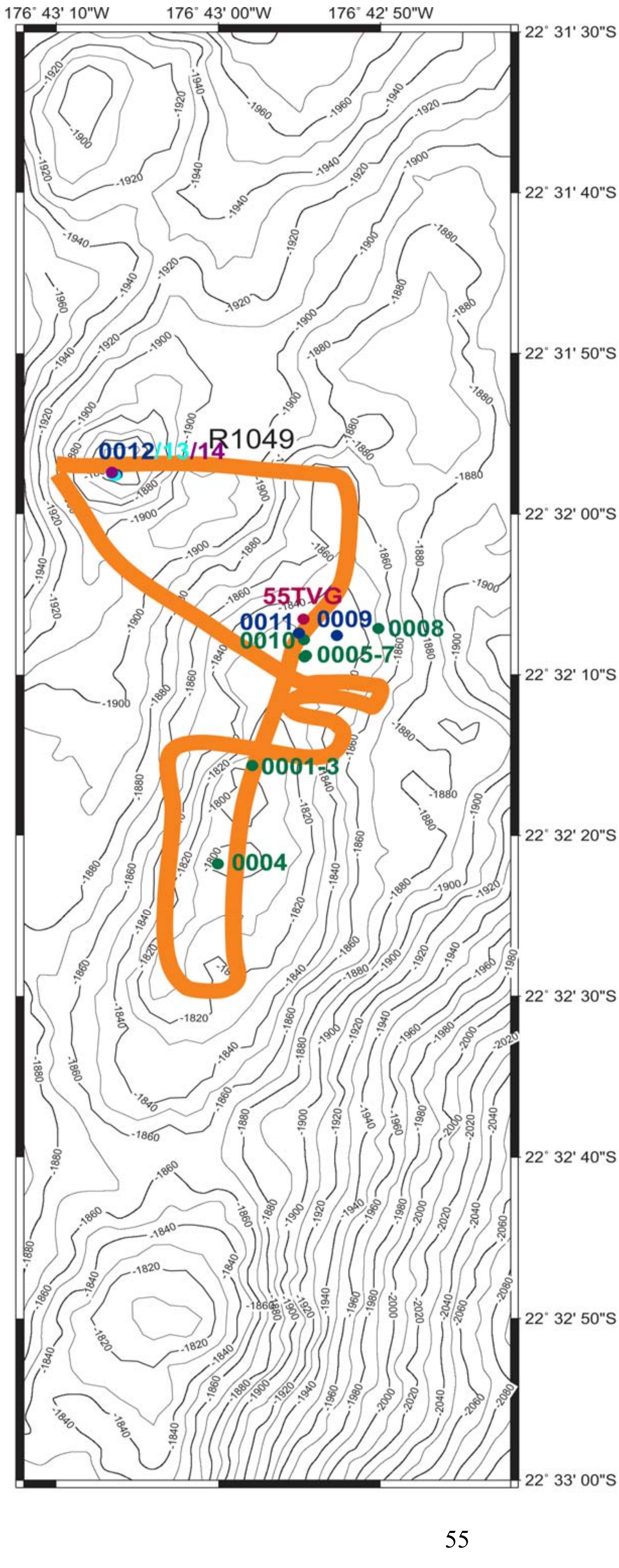


Fig. 5.34: Bathxmetry of the Hine Hina field, southern Valu Fa Ridge, with track of R1049 dive and sampling locations by ROPOS and TV grab (55TVG).

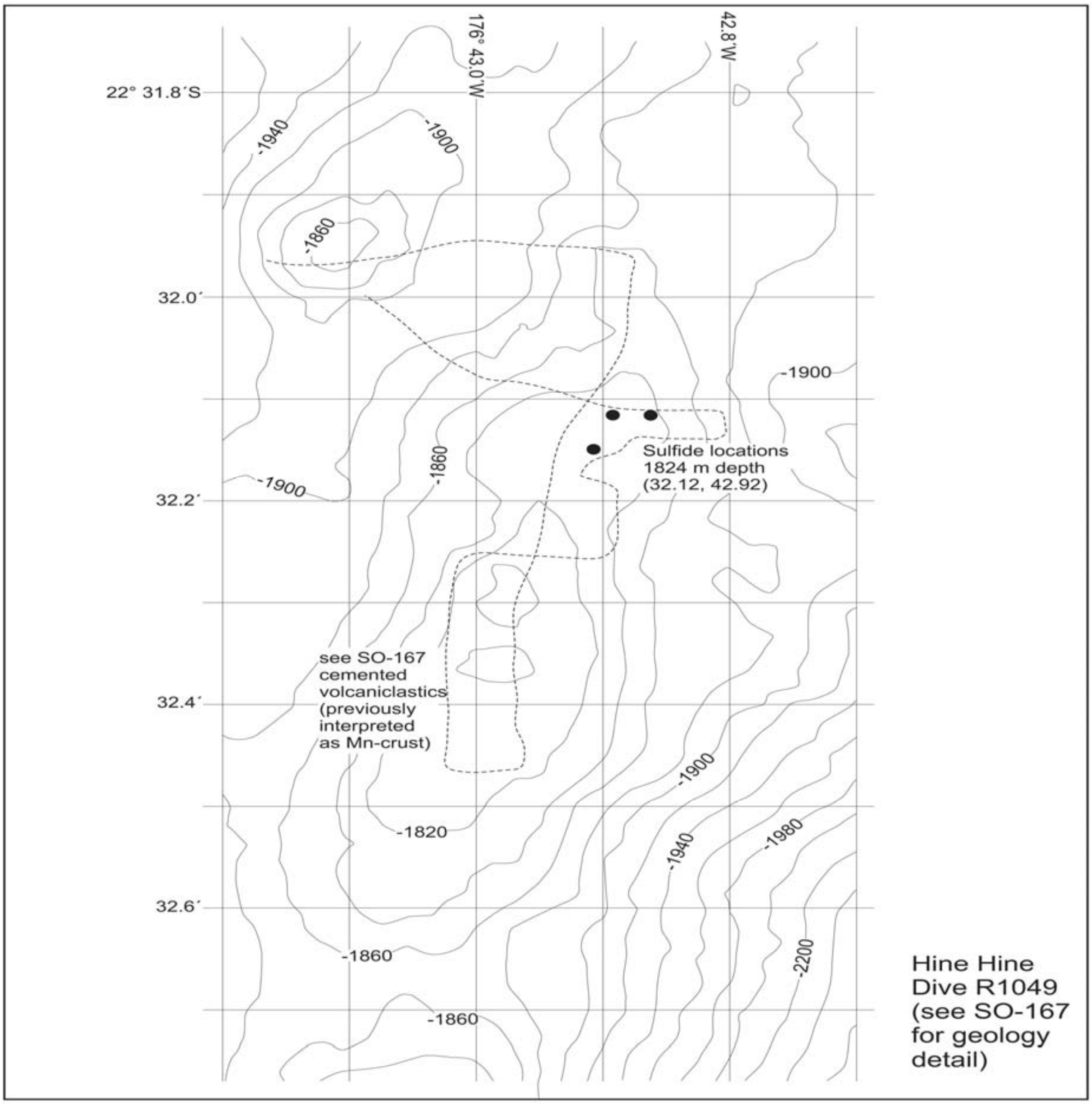


Fig. 5.35: Bathymetric map of the Hine Hina vent field, ROPOS track R1049, and locations of massive sulphide occurrences (55TVG).

5.6.3 Sampling

The Hine Hina field was sampled during ROPOS dive R1049 and by TV-grab station 55TVG (Figs. 5.34, 5.35). Samples include altered volcanic rocks of andesitic composition and few pieces of aphyric, vesicular unaltered basalt and black volcanic glass from a lava lobe. Alteration is associated with intense bleaching and pyrite impregnations. Volcaniclastic material (lapilli ash) is completely clay altered and indurated by oxyhydroxides, barite and pyrite. Blocks of massive sulphide were identified as talus blocks from chimney edifices (Fig. 5.36). Most samples are intensely oxidized to Fe-oxyhydroxides which form rims several centimetres thick. Most samples are Cu-rich and carry supergene secondary Cu minerals (atacamite, covellite, chalcocite, bornite). Chalcopyrite and pyrite occur in the center of the bigger fragments. Barite up to 5 mm in size is associated with most of the samples.

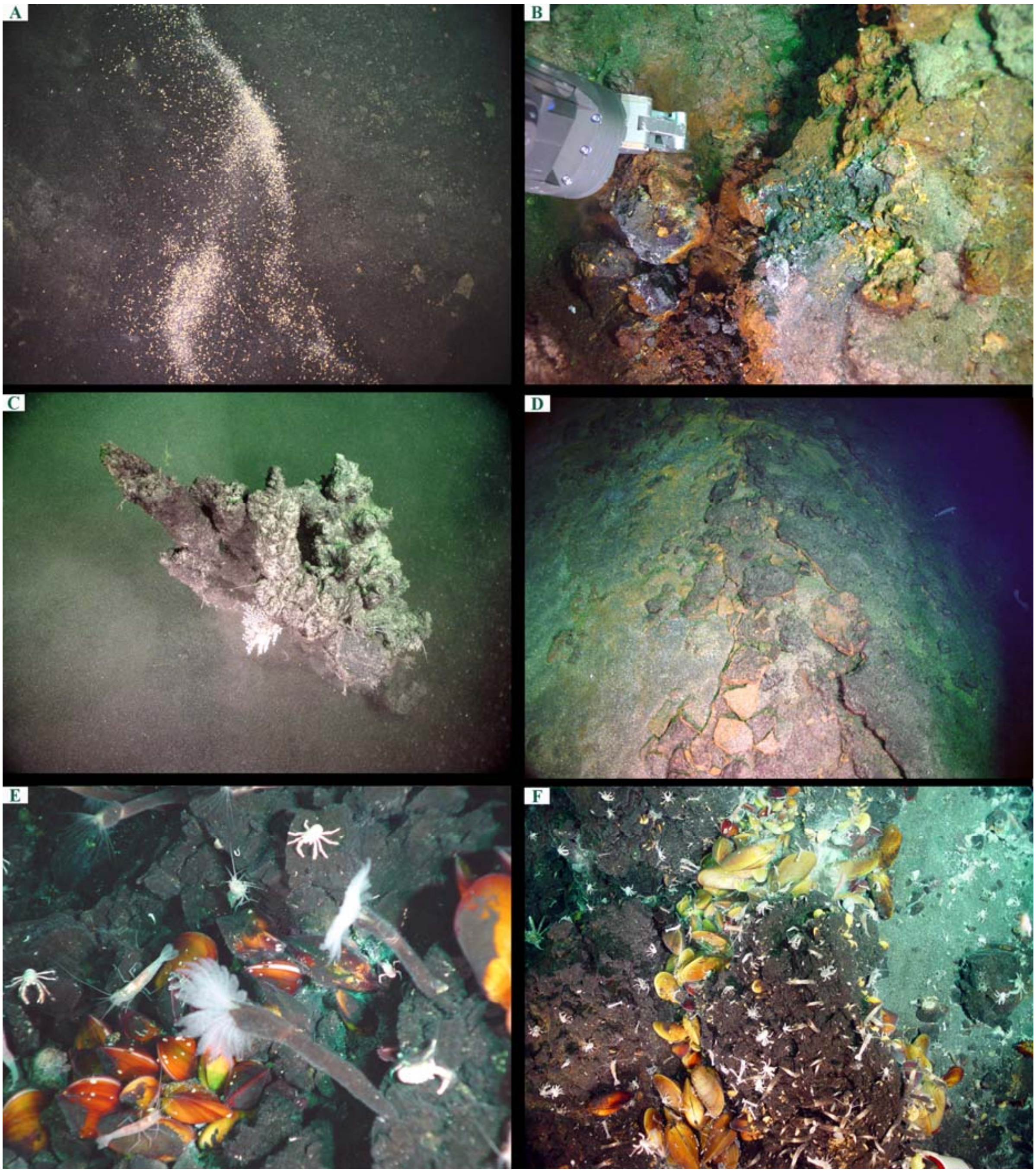


Fig. 5.36: Seafloor photos of the Hine Hina vent field. A: Small yellow shells trace a fracture and line fluid discharge within indurated volcanic ash. B: Sampling of a massive sulphide block, mainly consisting of Fe- and Cu-sulphides from an extinct chimney field. C: Inactive chimney. D: Ridge of volcaniclastic material, outlined by fractured Fe-oxihydroxide crusts. E, F: Various species of hydrothermal vent fauna, associated with low-temperature discharge (galathea crabs, limpets, bathymodiolus mussels).

5.7 Volcano 1, (21°09´S, 175°45´W), Southern Tonga Arc

5.7.1 Bathymetry and Structure

Volcano 1 is a large stratovolcano located in the southernmost part of the Tonga arc (Fig. 5.37). It was first mapped by the SO-167 cruise (Stoffers et al., 2003) and surveyed again with the Pisces submersibles during the SITKAP cruise in 2005 (Stoffers et al., 2006a,b). The recovery of hydrothermally altered volcanic scoria indicated ongoing hydrothermal activity in 2002 and the site was found to be hydrothermally active in 2003 during the TELVE cruise (Massoth et al., 2003b, 2007). Volcano 1 represents the northernmost and last target area of the SO-192/2 cruise.

Mapping during SO-167 revealed a large contiguous volcanic complex at 21°01'–21°31'S, 175°37–175°53'W (Fig. X). The complex features two major stratovolcanoes (Volcano 1 = 21°09'S, 175°45'W; Volcano 2 = 21°18'S, 175°42'W). Both are capped by summit calderas, and associated with a series of smaller satellite cones and volcanic ridges. Overall, the complex rises from a flat seafloor plain at ~1800 mbsl. A marked break in slope occurs near 1400 mbsl on both stratovolcanoes and defines the transition from the steeply sloping lavas of the central facies to the gently sloping volcaniclastic sediment of the distal facies. Volcano 1 is broadly symmetrical although elongated NW–SE, has a basal diameter of ~28 km and rises from a water depth of 1800 m to a summit at 65 m below sea level. A large oval caldera, with NW–SE trending long axis and a size of 7 x 4.5 km dominates the volcano summit. Most of the caldera rim is between 150 mbsl and 250 mbsl, with the highest areas predominating on the SE rim and the lowest to the SW at ~400 mbsl (possibly breached). The caldera floor is at 450 mbsl beneath the north, east and south caldera walls, and the inner caldera walls are generally 200–300 m high (Fig. 5.38, 5.39).

At least two episodes of post-caldera volcanism have occurred. During the first episode, a large post-caldera cone (V1P1) grew in the centre of the caldera and subsequently collapsed, leaving a gently east-sloping plateau bounded by a circular ridge 2.8 km in diameter that ranges from <50 m above the caldera floor in the east to 250 m above the caldera floor in the west. The caldera is interpreted to be largely infilled by the products of this cone and its collapse. Two smaller symmetrical cones have since grown between the western margin of the collapsed V1P1 cone and the western caldera rim. To the NW, the V1P2 cone has a diameter of 1.3 km, a summit at 150 mbsl, and rises 300 m above the caldera floor. To the SW, the V1P3 cone has a diameter of 1.2 km, a summit at 90 mbsl, and rises 350 m above the caldera floor. Tephra +/- lava flows from the V1P3 cone partly bury the SW quadrant of the remnant V1P1 cone, and a crater 100 m-deep and 300 m-wide occurs at its northern base. The V1P3 cone is interpreted as the youngest feature of the summit.

The SW flank of Volcano 1 is cut by a series of major faults, with the northernmost trending W–E with a throw of 100–200 m and the more southern ones trending SW–NE with a maximum throw of 100 m. These faults appear to govern both the northern and southern boundaries of the summit caldera, and also the location of the postcaldera V1P2 and V1P3 cones. The northern flank of Volcano 1 (to the north of the W–E fault) exhibits high relief attributed to outcropping lavas, whereas to the south the flanks are smoothed and presumably buried by volcaniclastics or caldera ejecta. A major satellite cone (V1FA) is located 11 km east of Volcano 1 and forms an 11 km long by 6 km-wide NNE-trending ridge with a summit at <300 mbsl. Smaller satellite cones occur on the lower NW flanks of Volcano 1 (V1FB = 5 km diameter, 1900–1150 mbsl; V1FC = 2 km diameter, 2100–1850 mbsl; V1FD = 1 km diameter, 1750–1550 mbsl), and along a north-trending lineament that cuts the eastern flank of the volcano (V1FE = 2.5 km diameter, 1500–1050 mbsl; and others that are <100 m in relief). A 3 km-long by 2 km-wide NE-trending ridge (V1FF) rising from 900 mbsl to 500 mbsl at the intersection of the north-trending lineament and a projection along the long-axis of the V1FA cone may be a flank vent whose NW side has collapsed, or possibly a remnant from an older mostly collapsed volcanic centre; this ridge is onlapped and partly buried by tephra from the caldera. Volcano 1 is joined to Volcano 2 by a 4 km-long and 3 km-wide flat-topped ridge, with the lowest point on the ridge being 550 mbsl. Hummocky terrain on both flanks of this ridge, but especially on the eastern side, suggests the ridge has a complex history involving multiple sector collapse events. It possibly represents the remnants of a relatively old volcanic centre associated with the V1FF ridge and other structures on Volcano 2 (V2FE, see below).

The petrography of Volcano 1 is dominated by basaltic andesite to andesite lavas and volcaniclastic deposits.

Hydrothermal activity at Volcano 1 is associated with neovolcanic structures to the west of the caldera (Fig. 5.40). The flank of a scoria cone was found during the SITKAP cruise to host widespread diffuse hydrothermal discharge. A chain of three explosion craters, as deep as 100 m, occurs on the flank of one of the scoria cones, and thick deposits of scoria and ash blanket the caldera floor in this area. Widespread diffuse hydrothermal venting, vigorous gas discharge, and thick beds of sulphur-cemented ash occur at water depths of 160–210 m in and around the explosion craters. A densely populated field of mussels (200 x 400 m) almost completely covers the seafloor in this area. The mussels (Bathymodiolus) occur where temperatures in the ash substrate are 30–70 °C, but patches with higher temperatures occur locally. But continuous streams of gas bubbles emanate from small holes and cracks in the sulphur-rich crusts. The water column throughout this area is clouded with white particles, most likely elemental sulphur from the vigorously discharging gas vents. Surrounding the chain of craters and on the nearby southern cone, the seafloor is almost completely covered by “snowy” white fields of filamentous bacteria. These areas are underlain by extensive Fe-oxyhydroxide crusts.

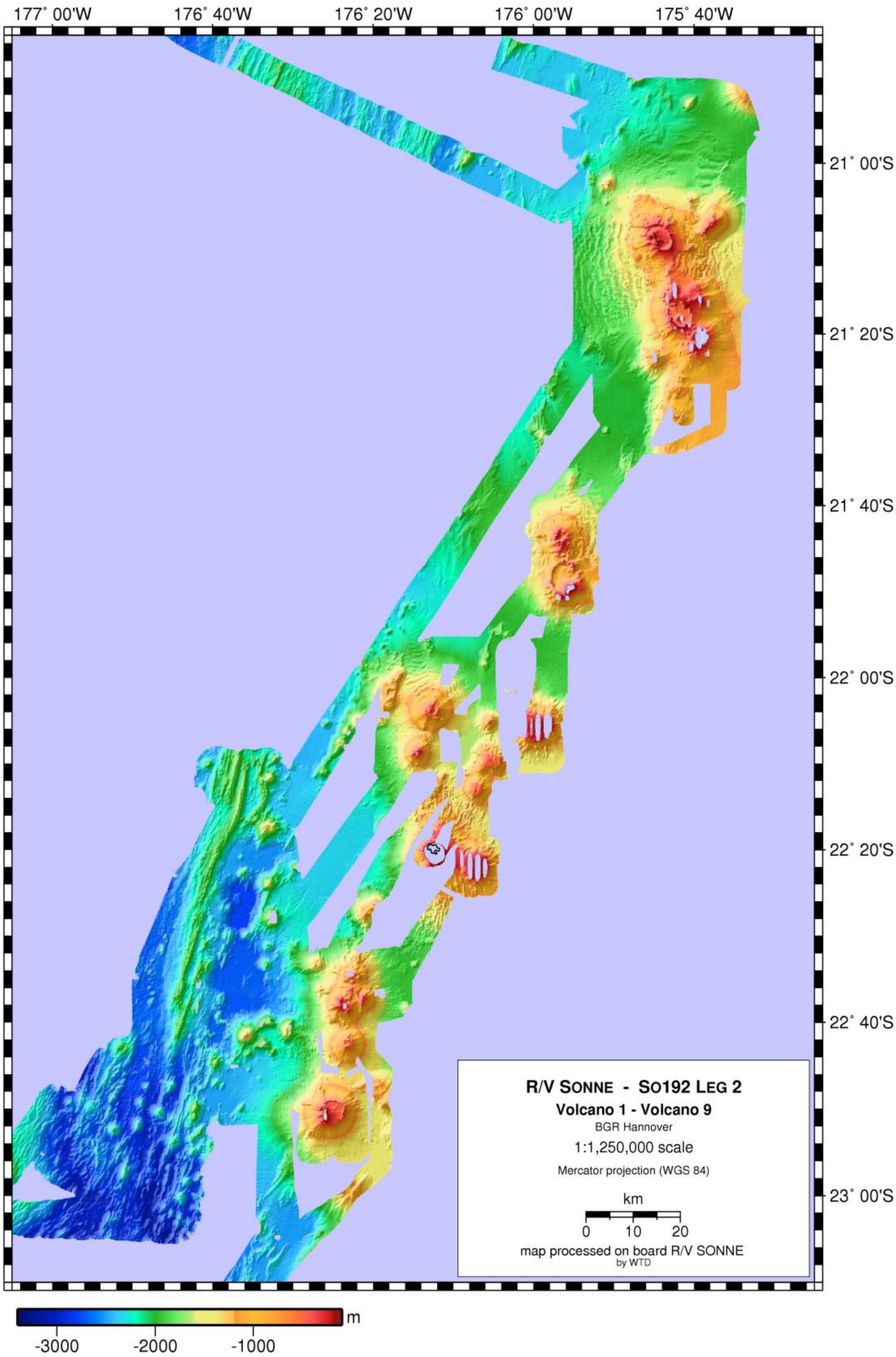


Fig. 5.37: Bathymetry of the southern Tonga island arc between Volcanoes 1 and 9. The southern Lau basin approaches the arc to within 25 kilometres. Despite the lack of a complete bathymetric map from this area, the general NW-SE extensional pattern is also obvious in the southern Tonga arc. The regional orientation forms an angle with the NNE-SSW trend of the Valu Fa ridge.

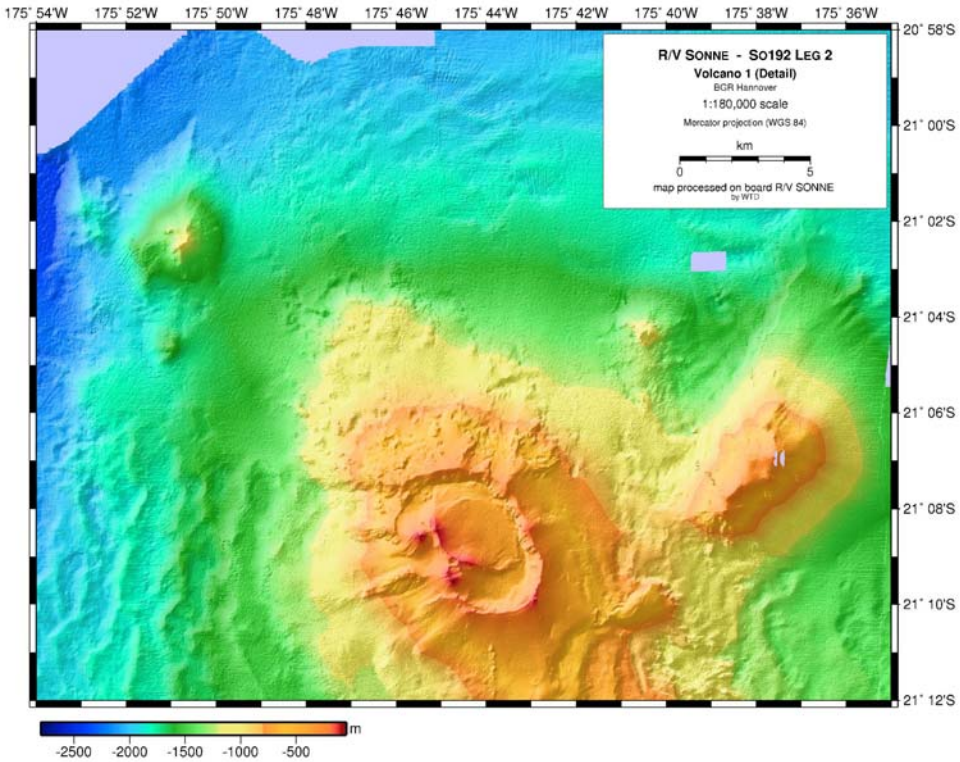


Fig. 5.38: Bathymetry of Volcano 1 and the area to the north, southern Tonga island arc.

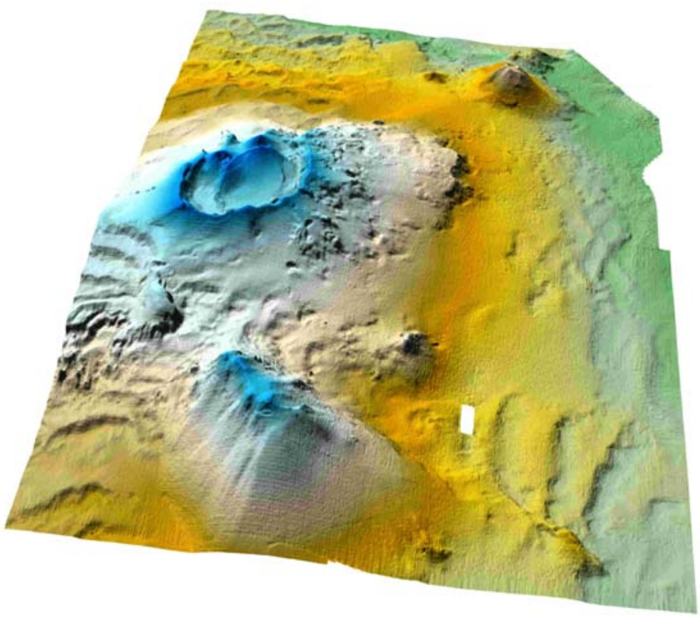


Fig. 5.39: 3-D bathymetric map of Volcano 1 and surrounding areas (view from NE to SW; refer to Figure 5.38 for latitude and longitude positions).

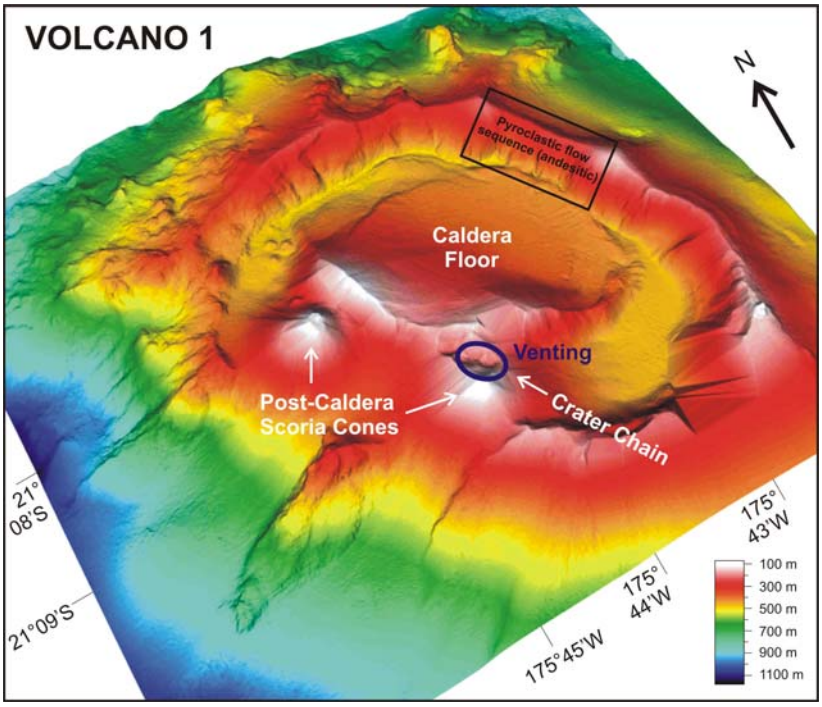


Fig. 5.40: Close-up 3-D bathymetric map of Volcano 1 (view from SW to NE).

5.7.2 ROPOS Operations

Volcano 1 was surveyed by ROPOS dives R1050, R1051, R1052, R1053, and R1054 (Fig. 5.41). Dive R1050 was used to locate and survey the mussel field and gas vents found during the SITKAP 2005 PISCES dives (Figs. 5.42, 5.43, 5.44). The dive started at the eastern end of the chain of craters (200 m water depth) and aimed at the survey of the chain, associated gas vents and mussel fields. This dive located successfully the main field at PISCES marker #43. A semi continuous field of mussels and gas venting was mapped along the southern edges of the easternmost and central pit craters. Venting at a maximum temperature of 70° C was found at two locations, but the high-temperature (151° C) vents measured in 2005 (marker #41) could not be found despite an extensive survey. As a consequence it is suggested that the volume of gas and the temperature of the vents noted during the PISCES dives had decreased since 2005. An area of abundant flatfish was surveyed on the north flank of the scoria cone adjacent to the Chain of Craters.

ROPOS dive R1051 focused again on the chain of craters and the NW flank of the scoria cone and surveyed in greater detail the eastern end of the mussel field, the western end of the second crater, the third crater. A traverse on the west flank of Volcano 1 and to the summit of the northwest scoria cone adjacent to the chain of craters aimed at the volcanological evolution of this edifice (Fig. 5.43, 5.44).

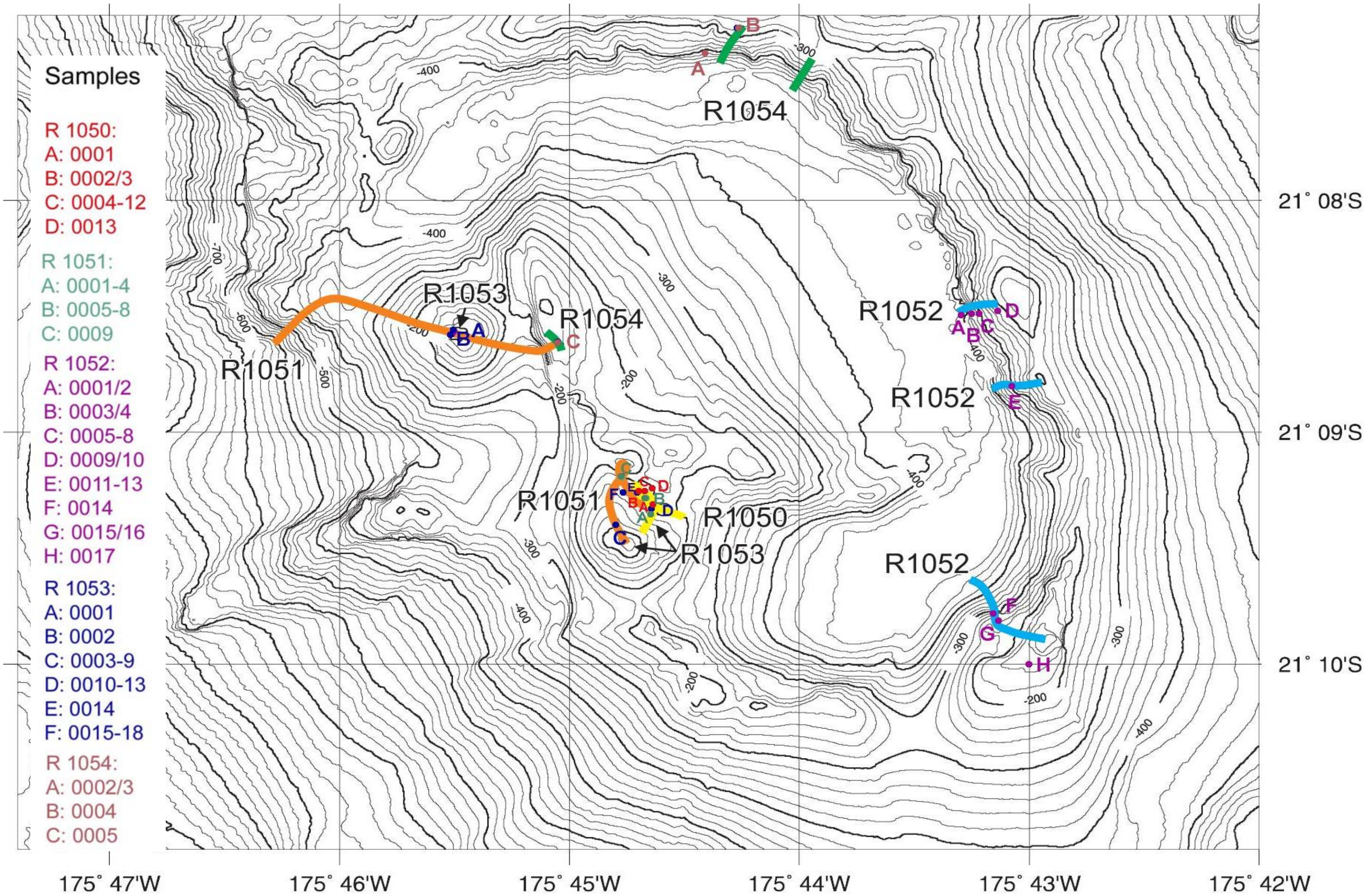


Fig. 5.41: Bathymetric map of Volcano 1 with ROPOS dive tracks and sample locations.

A survey of the western end of the central pit crater found a large area of Fe-oxide encrusted ash (>60 m diameter) with abundant bacterial floc, which was sampled for studies of Fe-oxidizing bacteria. No evidence of venting was found in the westernmost pit crater. A survey up the flank of the scoria cone south of the mussel field found patches of white bacterial mat and isolated patches of mussels on cemented ash blocks near the summit (100 m depth). The survey of the sector collapse on the flank of Volcano 1 occurred from a depth of 600 m up to the top of the northwest scoria cone (Fig. 5.45). A massive pillowed unit occurs at the deepest exposure in the scar of the sector collapse, revealing the interior of the basal section of Volcano 1. The remainder of this section comprises a steeply dipping dike complex about 150 m thick, which grades upward into a block-rich to fine volcaniclastic sequence (dikes were observed to break up into the overlying volcaniclastic units). White altered clasts were observed only in the lower part of the volcaniclastic sequence. The base of the scoria cone from 450 m to 350 m consists of blocky to coarse volcaniclastics intruded by numerous dikes. The upper part of the cone is covered by unconsolidated scoria, cinders, and local bombs. At the summit of the cone, near 100 m depth, large blocks are covered by bacteria. These may be the remnants of a dome at the top of the cone. The final leg of the dive examined a section of the lower part of the linear ridge (elongate scoria cone) northwest of the chain of craters. The lower part of the section consisted of coarse volcaniclastic material on a steep slope, with abundant white altered clasts and blocks. The upper part consisted of weakly bedded heterolithologic volcaniclastic units (Figs. 5.43, 5.44, 5.45, 5.46, 5.47).

Dive R1052 surveyed the caldera wall of Volcano 1. It examined three 250 m high sections of the eastern and southeastern inner caldera wall (Figs. 5.48, 5.49). Two sections of the eastern wall, 500 m apart, revealed massive coherent basalt (dike or sill complex) at the base (450 m depth). A bedded volcaniclastic unit was observed above the coherent base in both sections, capped by a thin section of finely bedded tuff. Above 400 m depth, the caldera wall is dominated by weakly bedded volcaniclastic units with abundant, densely packed (locally reversely graded) lithic blocks. These units may represent an early dome collapse. The entire section of block-rich volcaniclastic material is cut by numerous dikes subparallel to the caldera wall and locally by thin veins of white to green alteration. A third section of the southeastern caldera wall revealed a different stratigraphy, dominated by massive, columnar-jointed coherent flow or dike and sill complex from 400 m depth to the top of the caldera wall at <200 m.

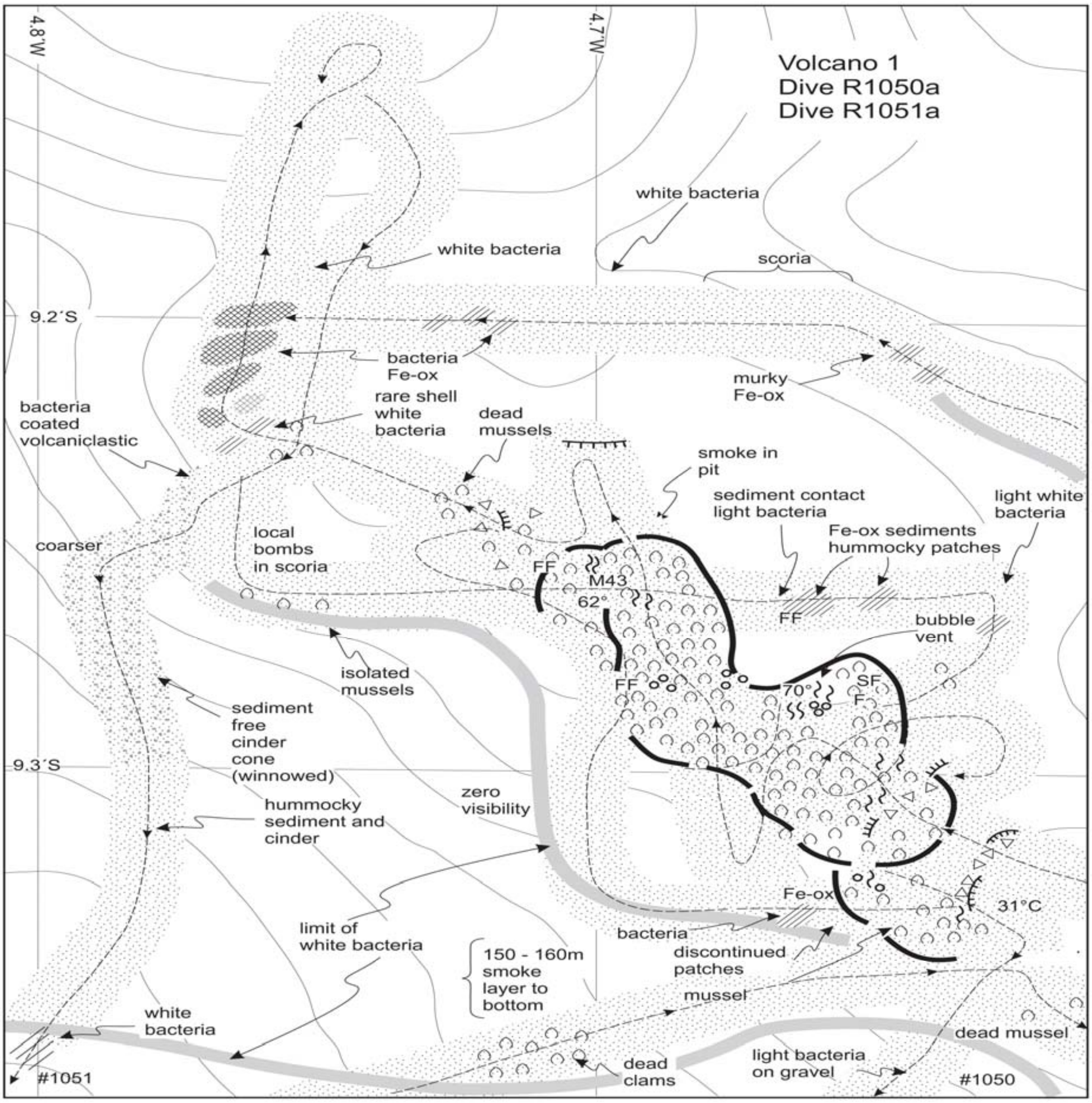


Fig. 5.42: Geological map of the hydrothermal vent area and extensive mussel fields at the southern edges of the easternmost pit crater of the crater chain in the southwestern part of the caldera at Volcano 1; dives R1050, R1051.

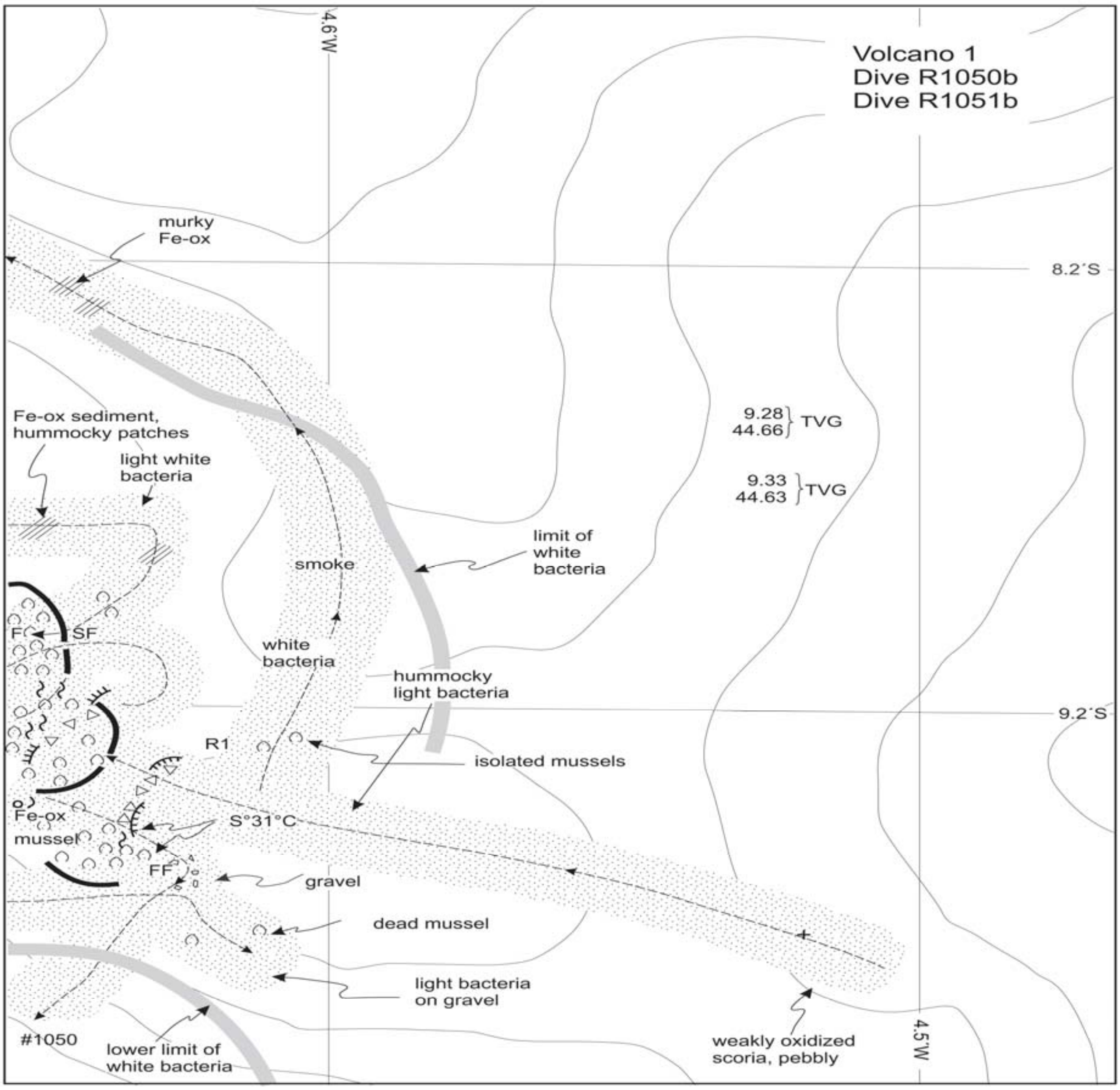


Fig. 5.43: Geological map of the hydrothermal vent area and extensive mussel fields at the southern edges of the central pit of the crater chain in the southwestern part of the caldera at Volcano 1; dives R1050, R1051.

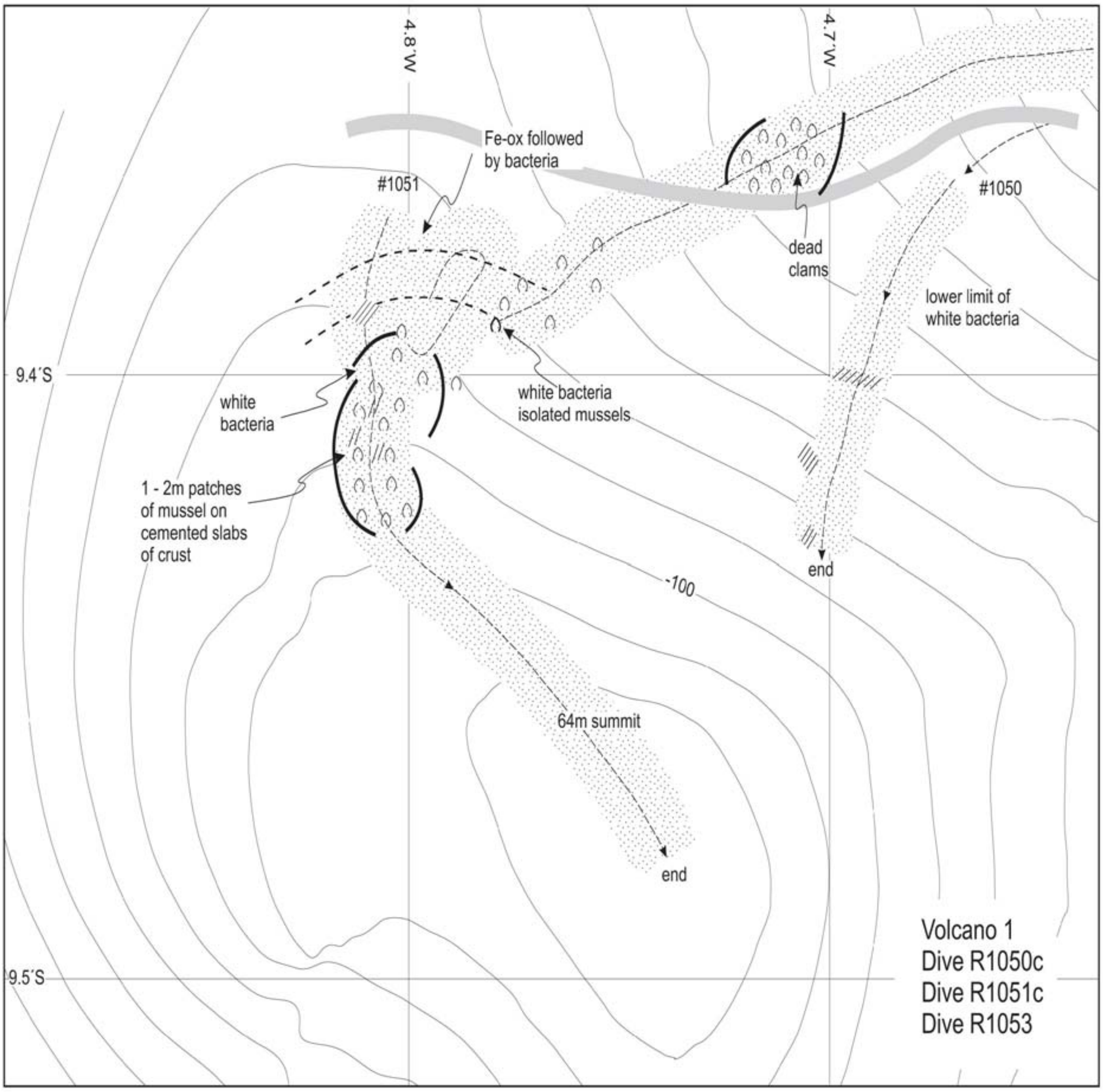


Fig. 5.44: Geological map of a hydrothermal vent area and patches of mussel at the northern flank of the scoria cone south of the mussel field at Volcano 1; dives R1050, R1051, R1053.

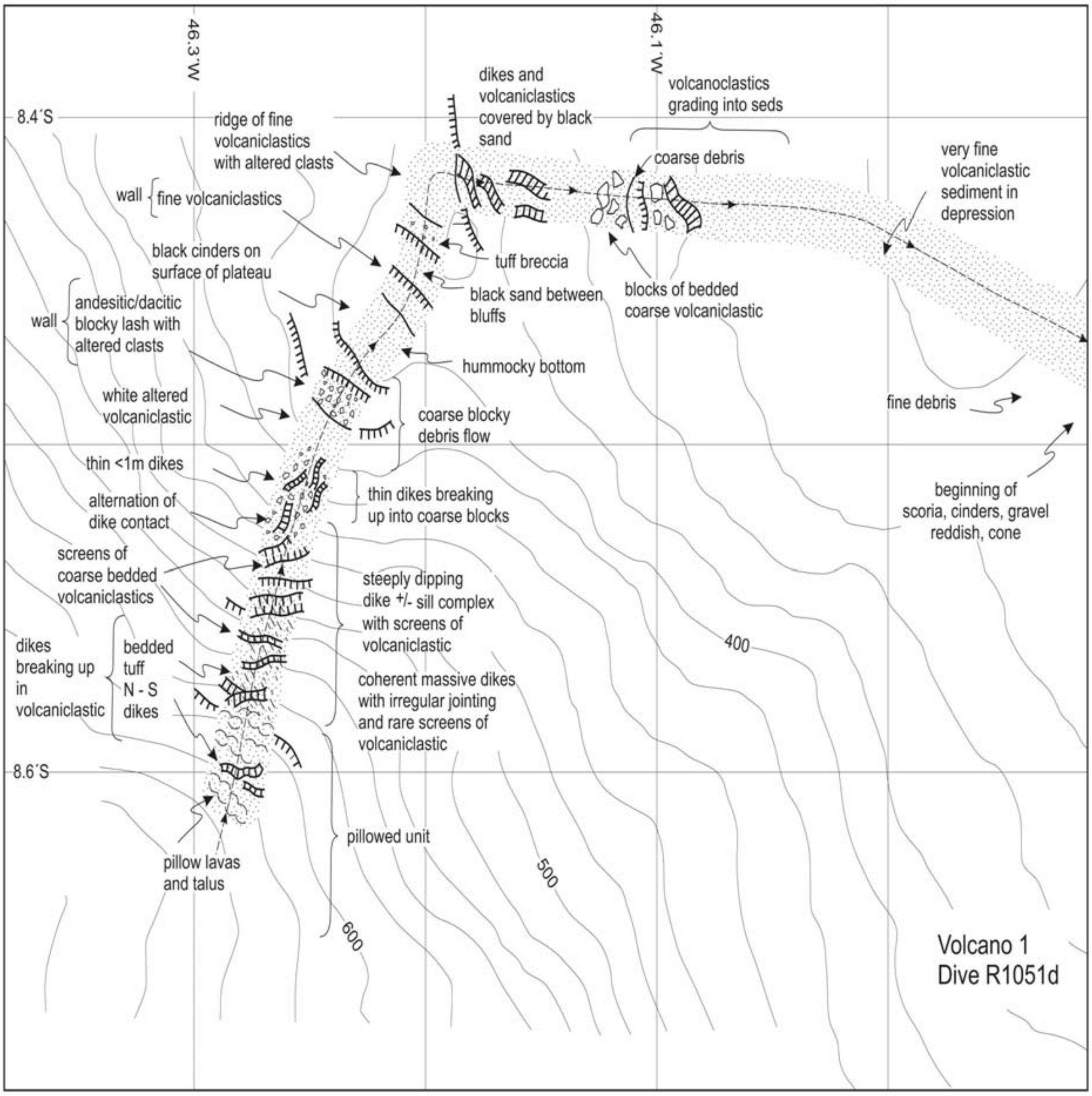


Fig. 5.45: Geological map of the sector collapse on the flank of Volcano 1 to the top of the northwest scoria cone at Volcano 1; dive R1051.

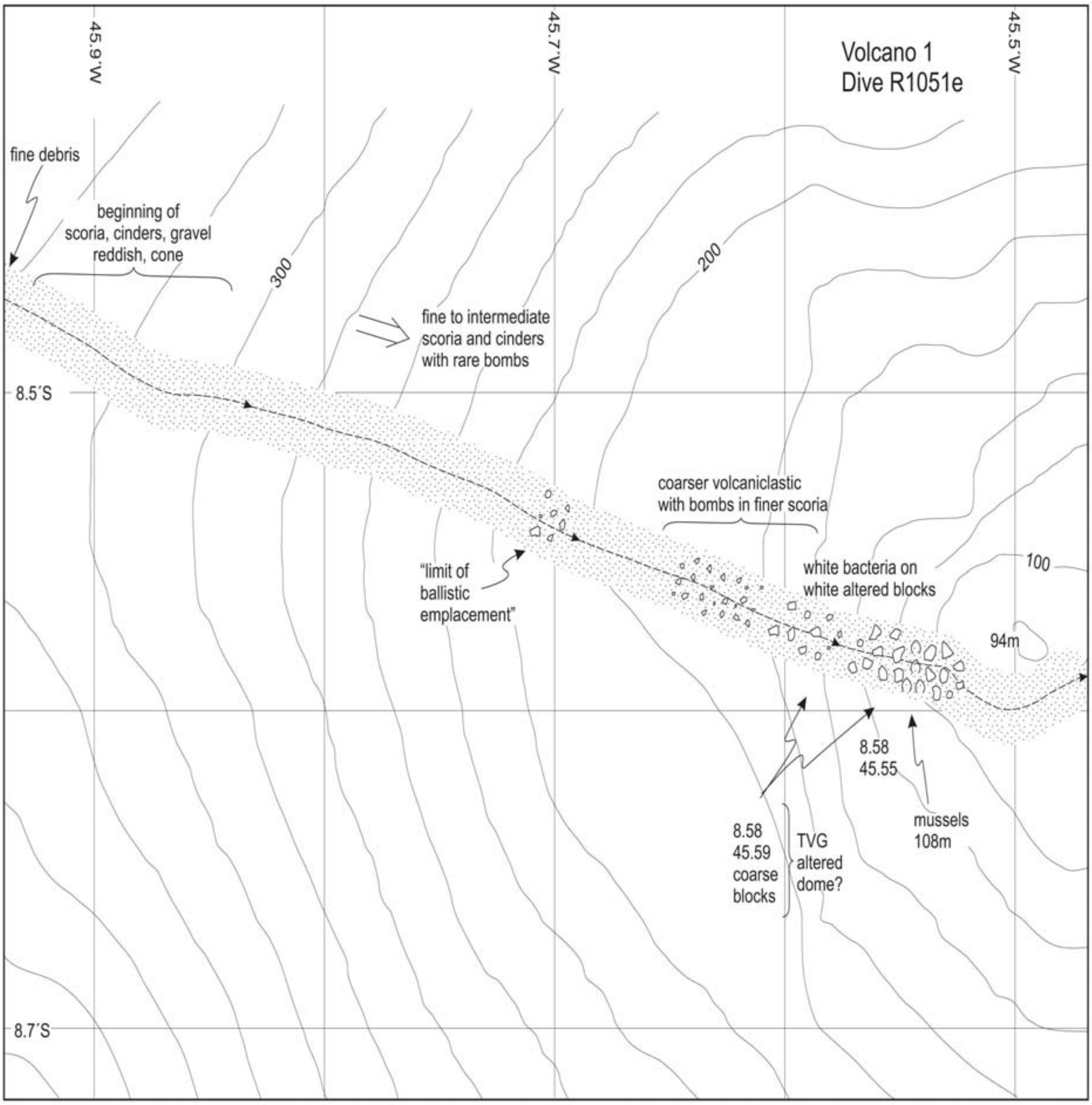


Fig. 5.46: Geological map towards the top of the northwest scoria cone at Volcano 1; dive R1051.

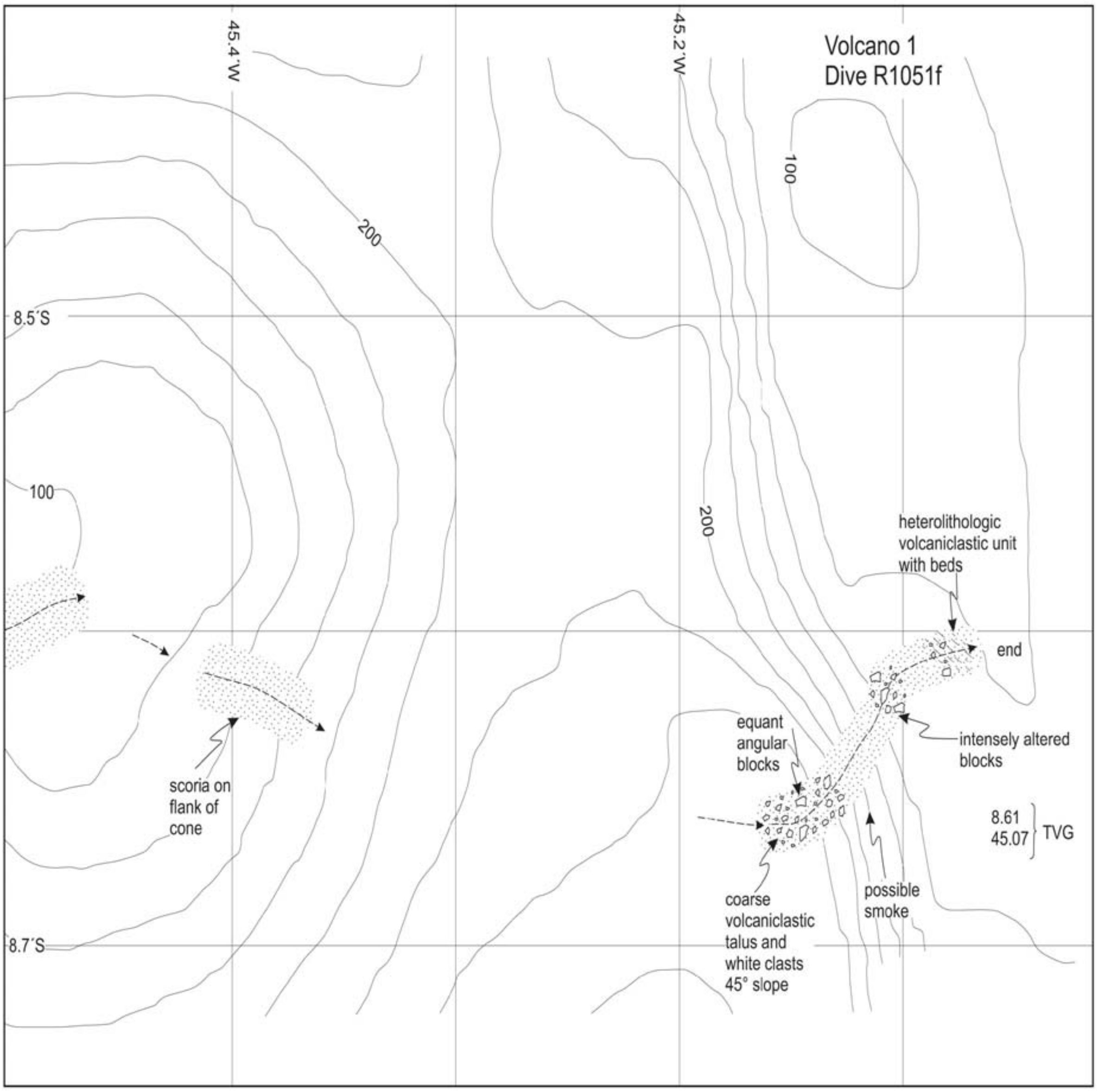


Fig. 5.47: Geological map of the lower part of the linear ridge (elongate scoria cone) northwest of the chain of craters; dive R1051.

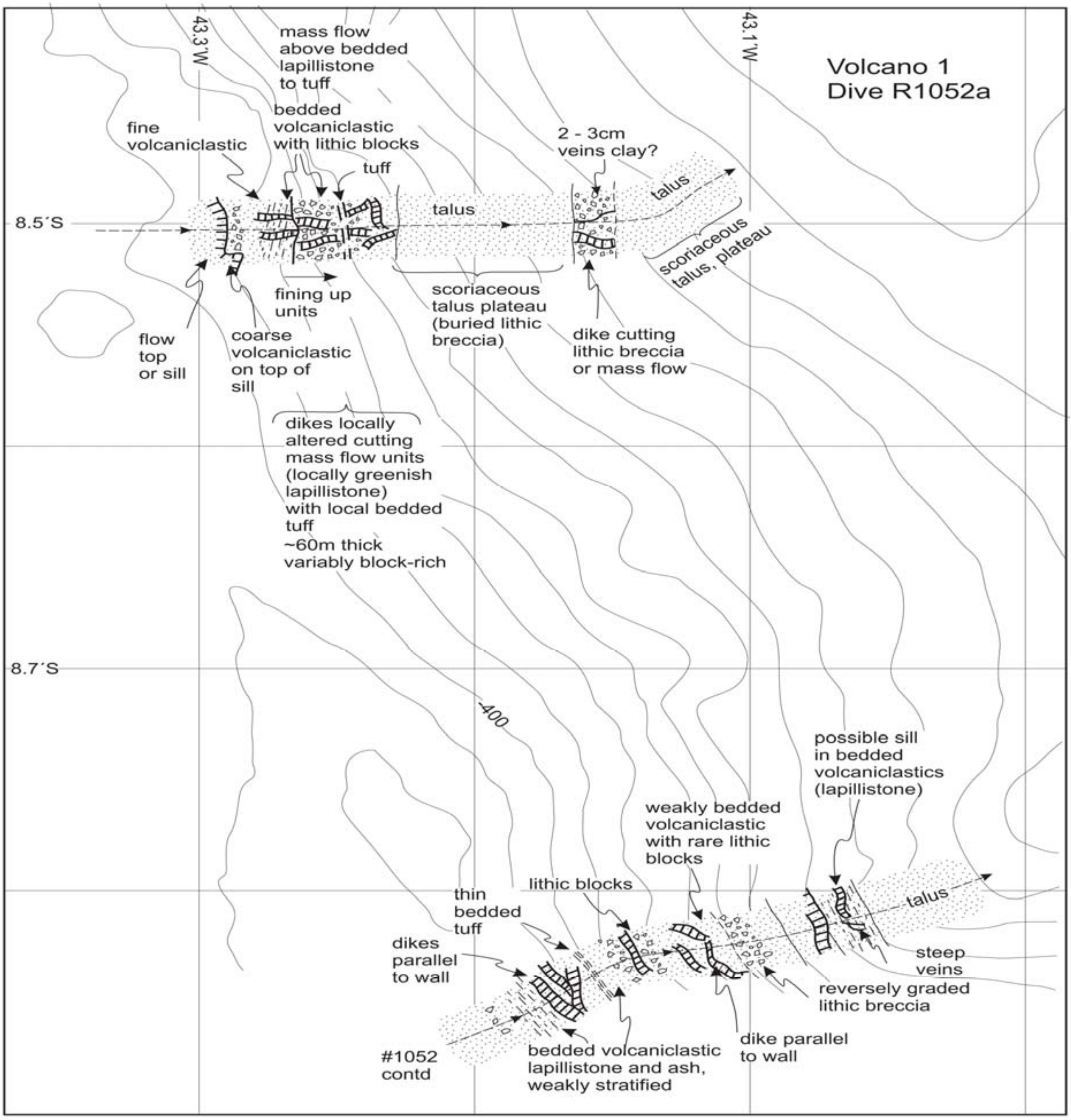


Fig. 5.48: Geological map of two 250 m high sections of the eastern inner caldera wall of Volcano 1; dive R1052.

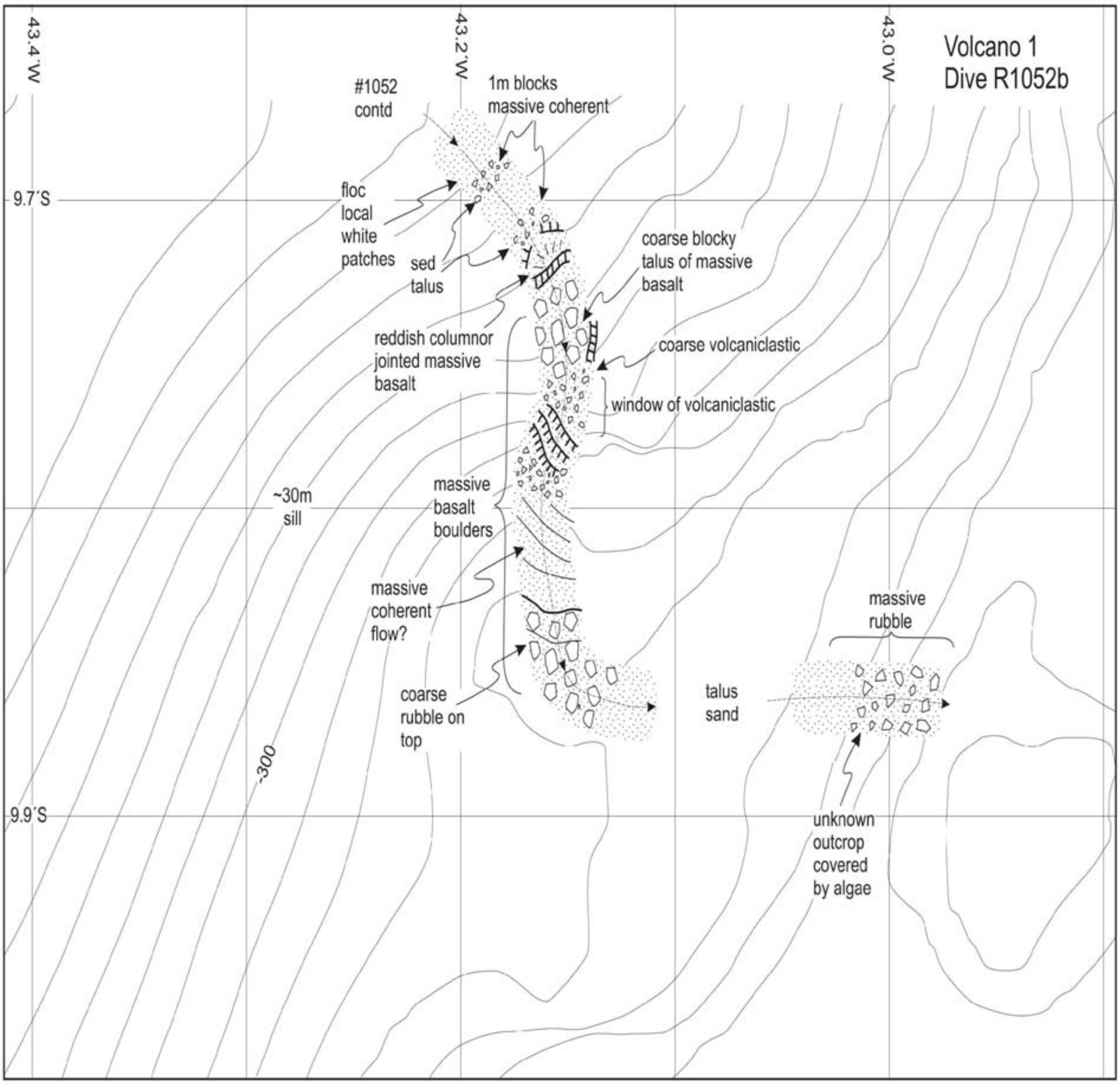


Fig. 5.49: Geological map of a 250 m high section of the southeastern inner caldera wall of Volcano 1; dive R1052.

The 250 m-high inner NE caldera walls expose steep outcrops of layered volcaniclasic sequences. These are typically 20-30 cm in thickness, and consist of alternating fine and coarse grained ash layers, partly mixed with boulder deposits. Andesitic pillowlavas are interbedded with these layers. The lowermost part of the caldera wall and much of the middle section is dominated by massive pillow andesite flows, commonly 5–10 m-thick. In contrast, volcaniclastic sediments are widespread throughout the lower central and upper central parts of the wall. These sediments also occur between some of the pillow flows. The volcanic deposits are subvertically cut by numerous dykes.

Dive R1053 concentrated on the shallow-water occurrences of mussels on the top of the two scoria cones on the flank of Volcano 1. The first part of the dive was at the summit of the scoria cone on the NW flank of the Volcano. A detailed survey was carried out of the mussel beds that occur on areas of sulphur-cemented ash near the summit (100 m). A survey of biology at the peak (64 m) was also conducted. The second part of the dive focused on the smaller area of mussels at the top of the scoria cone south of the main mussel field in the chain of craters. Detailed surveys of the mussels, algae, coral, etc. were carried out along with plankton tows and water-column filtering. The dive ended with water sampling at the sulphur vent in the main mussel bed, gas sampling at marker #43, and suction sampling of Fe-oxides at the west end of the central pit. The fish traps deployed during a previous dive were recovered. Previous TV grabbing at the location of the sulphur vent recovered massive native sulphur crusts, and the scar from the TV grab was photographed.

The last ROPOS dive during SO-192/2, R1054, consisted of two sections of the lower caldera wall at the northern end of the caldera and the survey of the linear volcanic ridge in the southern part of the caldera (Figs. 5.50, 5.51, 5.52). The lower part in both caldera wall sections (between 480 m and 380 m) consists of a finely bedded sediment unit more than 100 m thick, cut by rare dikes. This unit is overlain by the mass flow units observed in other sections of the caldera wall (consisting of coarse bedded volcaniclastics and lapillistone with interbedded fine tuff). The sediments appear to represent an older lithified unit that may be the basement on which Volcano 1 was constructed. The second part of the dive inspected the top of the linear ridge adjacent to the two scoria cones on the south side of the caldera (Fig. x). This was the location of a TV grab that recovered fresh volcanic bombs. Two successions of scoriaceous material were observed; a lower fresh black scoria (possibly the edge of a recent cinder cone) and an older, reddish oxidized scoria. The impression is that the linear ridge may be a series of overlapping cinder cones developed along the length of an eruptive fissure, possibly similar to the feature on which the chain of craters is located. No evidence of recent hydrothermal activity or degassing was noted, suggesting the absence of any heat associated with the fissure.

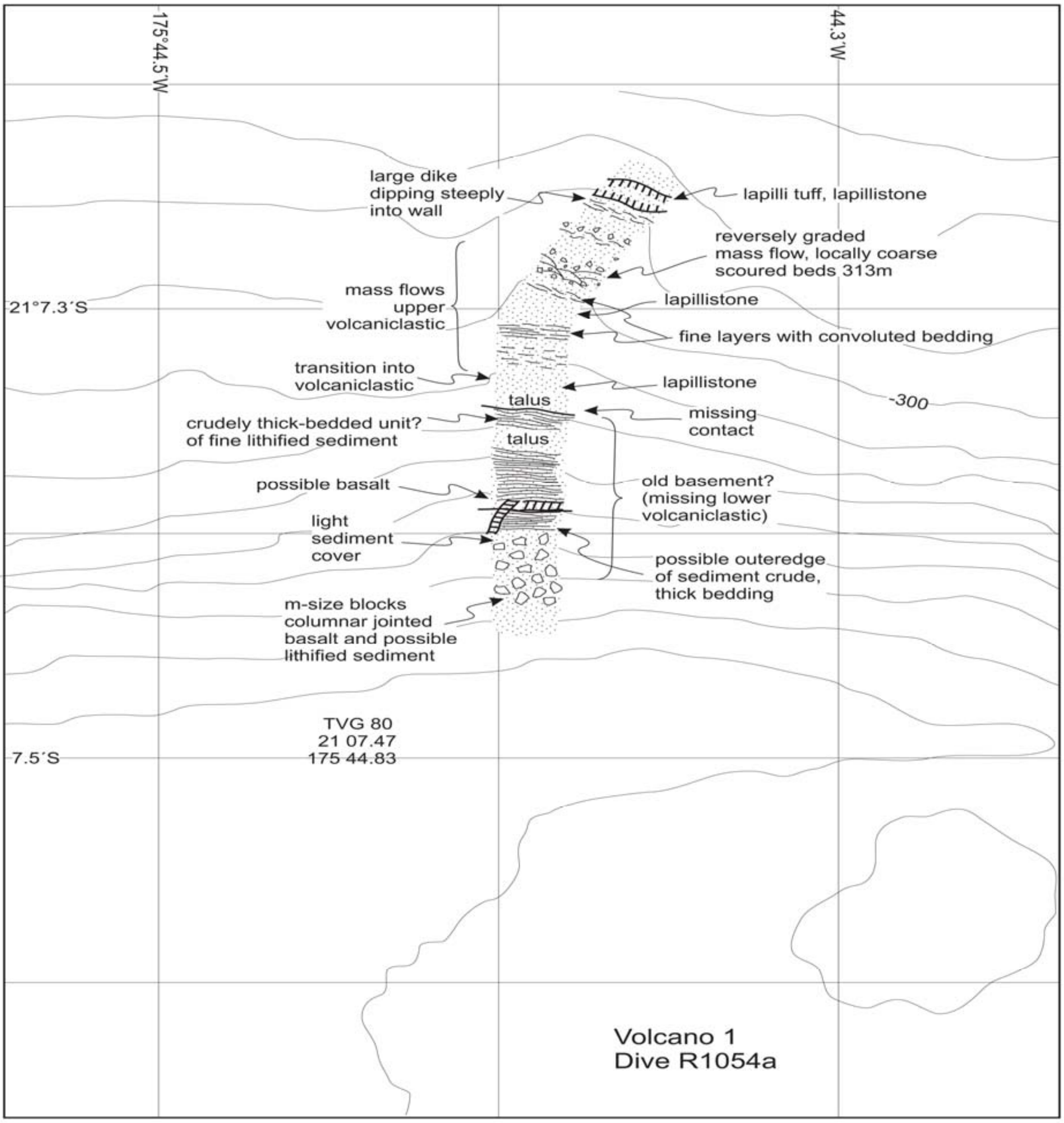


Fig. 5.50: Geological map of a section of the lower caldera wall at the northern end of the caldera of Volcano 1; dive R1054.

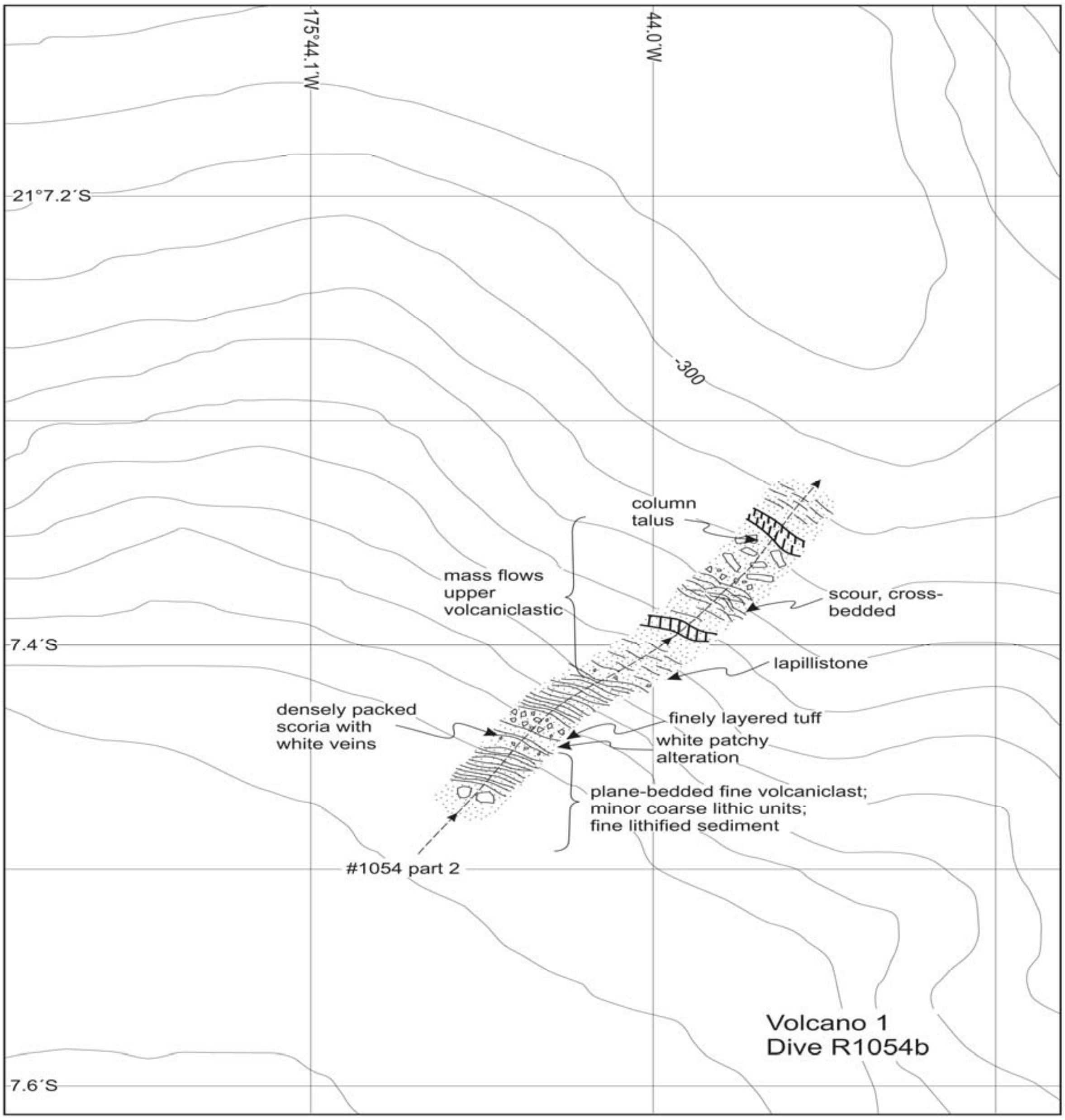


Fig. 5.51: Geological map of a second, more easterly section of the lower caldera wall at the northern end of the caldera of Volcano 1; dive R1054.

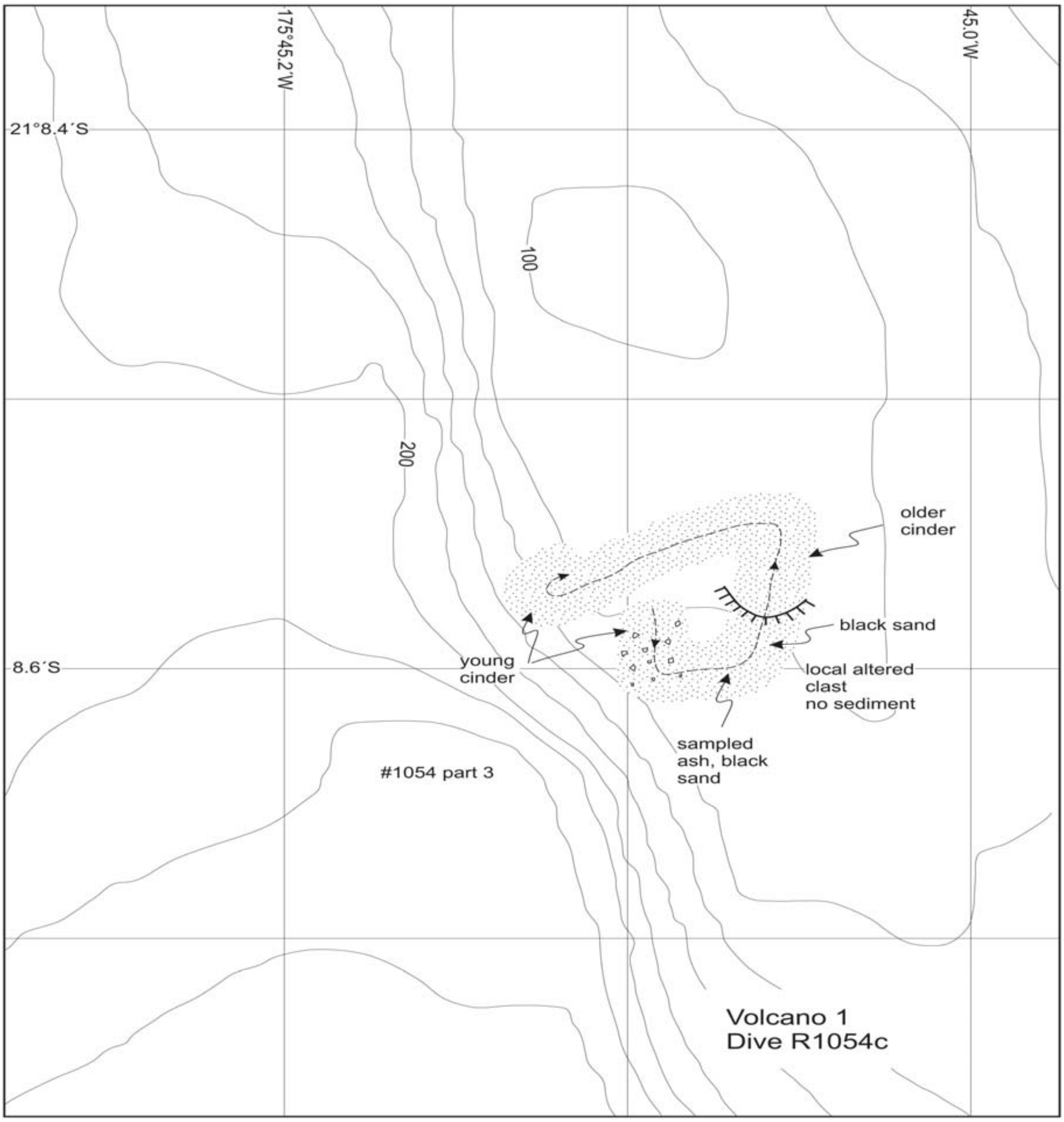


Fig. 5.52: Geological map of the linear volcanic ridge in the southern part of the caldera of Volcano 1; dive R1054.

5.7.3 Sampling

Volcano 1 was sampled during ROPOS dives R1052, R1053, R1054, and by 12 TV-grab stations (59TVG, 60TVG, 64TVG, 65TVG, 67TVG, 71TVG, 72TVG, 73TVG, 74TVG, 78TVG, 79TVG, 80TVG). Seafloor observations and sampling operations are shown in Figure 5.53.

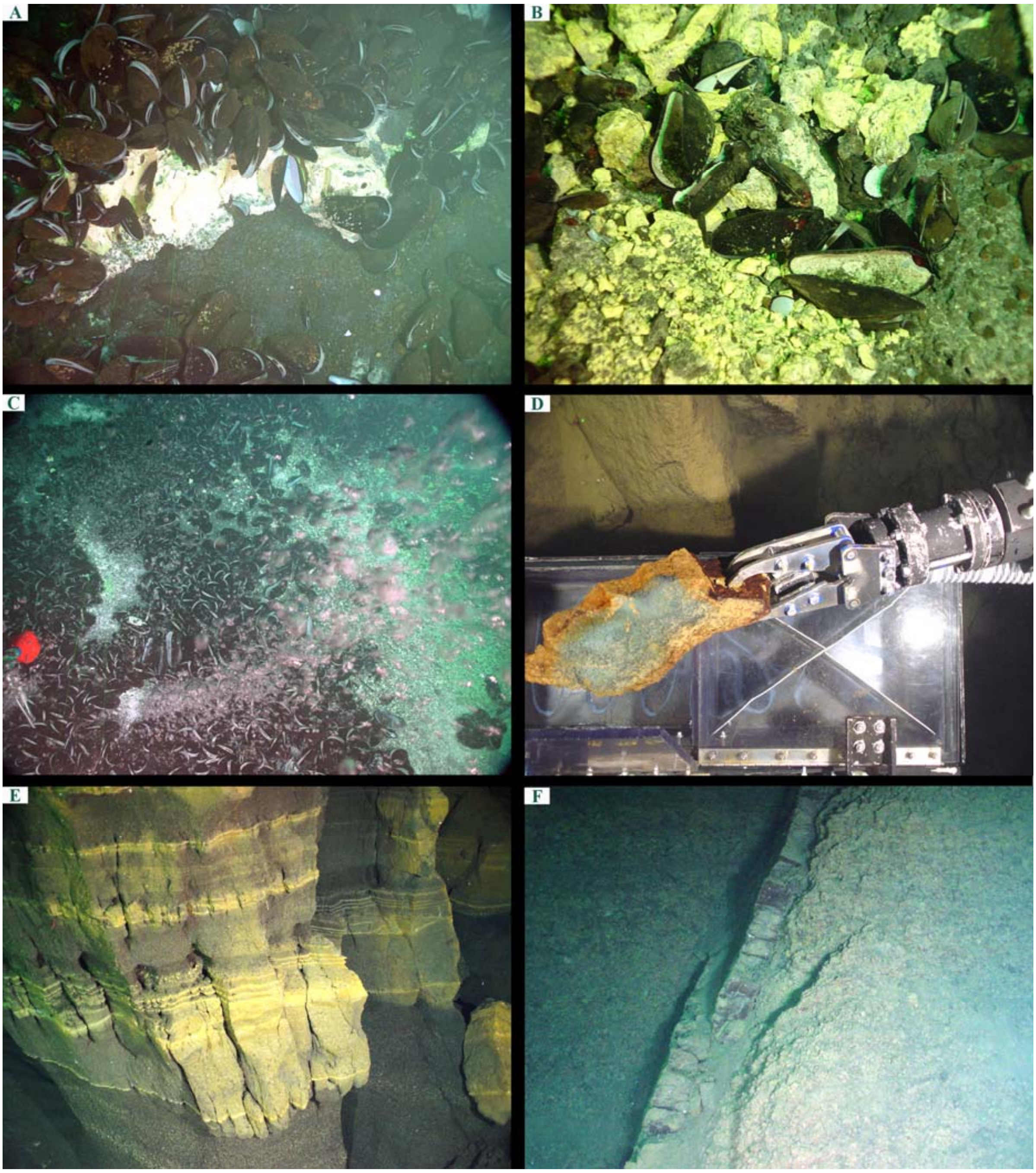


Fig. 5.53: Seafloor photos of Volcano 1. A, B: Native sulphur precipitates from low-temperature fluid discharge forming blankets of several cm to dm thickness. The sulphur is interbedded with volcaniclastic material and densely overgrown by bathymodiolus mussels. C: Intense discharge of gas bubbles at the Mussel Field. ROPOS is preparing a gas tight fluid sampling with a funnel tool. D: ROPOS sampling of a piece of consolidated fine-grained volcanic ash. The rock shows intense weathering on the outside. E: Nearly vertical caldera walls with layered volcaniclastic deposits. F: Basaltic dike cutting through fine-grained volcaniclastics.

The rock samples include layered volcaniclastic material with angular to subangular clasts, partially cemented lapilli ash, weakly consolidated volcanic ash, vesicular and plagioclase-phyric basaltic pillows and flows, massive angular block of phyric and vesicular basalt from a dike/sill complex, porphyritic basalts, vesicular, plagioclase-phyric volcanic bombs, most with distinct glassy rims, blocks of plagioclase-phyric basaltic andesite, plagioclase-phyric and occasionally highly vesicular andesitic to dacitic lava flows, vesicular aphyric andesite, relatively fresh lava with thin glass selvages and rims, glassy fragments, glassy and highly vesicular pumice.

Hydrothermal activity in the surroundings of active vents is evidenced by variable alteration of volcaniclastic material including staining by Fe-oxyhydroxides and the bleached interior with contorted vein-like fabrics. Lapilli ash shows induration and Fe-oxide staining, and is impregnated and overgrown by native sulphur, pyrite and authigenic clays. TV grabs in the center of the mussel field (near marker #43) recovered crusts of massive, fine-grained pyrite and marcasite, intergrown with euhedral crystals of native sulphur. TV grabbing at the location of the sulphur vents recovered massive native sulphur crusts of 40 cm thickness, with crystals of up to 7 cm in size. The sulphur is interbedded with volcaniclastic sediments which occur as thin black layers within the massive or crystalline native sulphur.

6. HYDROTHERMAL VENT AND PLUME CHEMISTRY – FLUID SAMPLING PROGRAM

Reiner Botz, Mark Schmidt, Leigh Evans, Matt Leybourne, Christian Ostertag-Henning, Markus Rauch, Ulrike Westernströer

6.1 Introduction

The Tonga-Kermadec ridge is an intra-oceanic arc, which represents the boundaries between converging lithospheric plates. These volcanic arcs demonstrate a potentially extensive source of shallow (< 2 km below seawater level) hydrothermal activity. During the last years many high-temperature hydrothermal vent fields associated with these volcanoes were found in the areas of Kermadec and Tonga arc (de Ronde et al., 2001; Massoth et al., 2003; Stoffers et al, 2005; Massoth et al., submitted). Hydrothermal discharge from volcanic arcs is different from that of MOR and the chemical composition of venting fluids and associated mineralisation provide a unique opportunity to clarify various element recycling processes at arc volcanoes (de Ronde et al., 2001; Massoth et al., 2003; Lupton et al., 2004; Embley et al., 2006).

Some of the numerous arc volcanoes lined up at the Tonga-Kermadec arc could be directly described and sampled e.g. by using the submersibles PISCES IV and V (Stoffers et al., 2005). The high-temperature hydrothermal system at Volcano 19, located at the southern end of the Tonga arc e.g. has two large hydrothermal fields with emanating fluids showing phase separation between 390 and 550 m water depth and temperatures up to 265°C (Stoffers et al., 2005). Venting fluids formed chimneys of barite and anhydrite, which reach heights of more than 10 m. The fluids of Volcano 19 are slightly acidic (pH 5-6) and show concentrations of dissolved gas of up to 15 mmol/kg.

Volcano 1 is situated further north. Its summit is located 65 m below sea level. Widespread diffuse low-temperature venting (pH 3-6) occurs with variable gas discharge (Massoth et al., 2005). Gas bubbles, rich in CO_2 and H_2S were observed ascending from many small holes and cracks in sulphur-rich crusts. Gas concentrations (up to 137 mmol/kg) in fluids at about 200 m water depth are relatively high compared to other arc volcanoes (Stoffers et al., 2005; Lupton et al., 2005).

The southern Kermadec arc has a significant number of hydrothermal active submarine volcanoes. Volcanoes which host hydrothermal venting fields are Clark, Tangaroa, Rumble III, IV, Rumble II West, Healy and Brothers. Several volcanoes show discharge with a gas-rich component like H_2S for Rumble III, IV and the cone of Brothers (de Ronde et al., 2001). Helium isotopes of hydrothermal gas give evidence about mantle contribution to the hydrothermal fluids. Additional information from stable isotope data of methane and carbon dioxide measured in vent gases can identify subsurface contributions derived from biogenic processes, fluid/rock interactions, or sediment (organic matter) alteration (Botz et al., 1999). Stable C-isotopes of CO_2 e.g. from vents in the Bay of Plenty show values from –2.4‰ to –5.5‰ PDB, which is indicative for a shallow magmatic source (Botz et al., 2002). On the other hand, carbon and hydrogen isotopic composition of methane and the occurrence of higher HC's give evidence that HC-production was controlled by high-temperature maturation of sedimentary organic matter (Botz et al., 2002). Liquid long-chained and significant proportions of gaseous hydrocarbons were also determined in sediments and fluids of the Bay of Plenty. The hydrocarbons derived from thermal organic matter degradation (Botz et al., 2002). Oil and wax impregnated sediment samples where associated with As-Hg mineralisation and liquid mercury, which indicates the high potential of the hydrocarbon/metal-rich hydrothermal fluids in forming ore deposits (Stoffers et al., 1999).

6.2 Objectives

1) Identification of (organo)metallogenetic and (bio)geochemical characteristics of hydrothermal fluids along the Tonga-Kermadec arc, starting at Calypso vent field (37°41'S) where continental crust has an input on hydrothermal vent chemistry, ending at the Tonga arc at Volcano 1 (21°09'S) where thin oceanic crust is subducted.
2) Mobile metal/trace elements will be measured in fluids and compared to mineralisation products and fluid inclusion composition. Metal enrichment processes will be investigated. Stable isotope compositions of fluids, minerals and fluid inclusions of e.g. O, H, S, and C will be determined to clarify sources and evolution of fluids during phase separation and mineral precipitation.
3) Endmember fluid chemistry of hydrothermal fluids along the arc will be compared to known vent chemistry of Mid Oceanic and Back Arc hydrothermal fields. The investigation will allow us to indicate deeper physico-chemical processes of magma degassing, fluid mixing, phase separation, mineral/ore precipitation.
4) The comparison of new vent characteristics with published data will provide insights in possible temporal variations of the chemistry at these sites.
5) Determination of plume chemistry and caldera water chemistry will provide information about flux intensities and secondary degradation processes of hydrothermal fluids and gases (e.g. CH_4).

6.3 Methods

Gas sampling

Vent fluid samples for the analysis of dissolved and free gases were collected using gas-tight titanium bottles from PMEL/Newport (GT in Appendix 7, Table 1). Up to 4 of these gas-tight bottles were mounted on ROPOS with the inlet of each gas-tight bottle connected to the tip of the magnum claw of ROPOS with heat resistant PEEK (polyetheretherketone) tubing. The 150cm^3 internal volume of each gas-tight bottle was evacuated to a high vacuum prior to each dive. After recording the vent fluid temperature at the tip of the magnum claw the appropriate gas-tight bottle was triggered with a hydraulic actuator, causing the fluid to be rapidly drawn through the PEEK tube into the evacuated bottle. During some dives the gas tights were also connected with PEEK tubing to a funnel device to collect bubble streams. There were concerns about the accurate temperature measurement using the ROPOS T-sensor. Temperatures measured with the probe were usually 4 °C higher than the calibrated CTD T-sensor. T-calibration of the ROPOS T-sensor will be provided after the cruise.

After each dive the samples were processed on a seagoing high vacuum line. The sample, consisting of a mixture of fluid and gas, was dropped into an evacuated chamber holding a small amount of an acidic salt which causes quantitative degassing of CO_2. Then a hand-operated bellows pump was used to pump the released gases through a drying trap held at -

60ºC. The dry gases were pumped into a calibrated volume, and the pressure accurately measured using a capacitance manometer. Then splits of the extracted gases were sealed into glass ampoules for later analyses either by gas chromatography or mass spectrometry. The gas species to be analysed in shore-based laboratories include helium and helium isotopes, neon, argon, nitrogen, carbon dioxide, $\delta^{13}C_{CO2}$, $\delta^{18}O_{CO2}$, methane, $\delta^{13}C_{CH4}$, δD_{CH4}, and hydrogen sulphide.

Fluid Sampling

Major titanium bottles from MBARI Moss Landing (Major MB, Appendix 7, Table 1), were used for hydrothermal fluid sampling. The bottles with an internal volume of 750 cm^3 were stored during ROPOS dives in the frontal bio box. Both "kraft" arms of ROPOS were used to operate the Majors. The right arm placed the sampler that the titanium snorkel, which was fixed to the Major inlet, was pointing into the venting fluid. The pre-stressed sampler was triggered by a hydraulic piston attached to the ROPOS arm. The fluid was then slowly sucked into the sampler by the force of an expanding spring. Onboard sampling was done by pressing the fluid through the sampler outlet valve into different pre-cleaned sampling vials. Sub-samples were stored and transported at room temperature, +4°C, and –60°C, respectively, for later measurements. The fluids will be analysed with respect to their concentrations of major and trace elements, nutrients, organo-metallic compounds as well as the stable isotopic compositions of water, dissolved inorganic carbon, SO_4^{2-}, and H_2S. Alkalinity, salinity, pH and Fe^{2+} was measured onboard directly after fluid recovery (Appendix 7, Table 1).

Plume/Water sampling

Water samples were also taken in the water column at selected depth above hydrothermal vent fields by using a SEABIRD-CTD attached to a Niskin bottle rosette. The physical/chemical parameters (temperature, sound velocity, conductivity, light transmission, pressure, oxygen content) were recorded online and sampling depths were selected considering mainly transmission and temperature excursions. After recovery the waters in the Niskin bottles were sampled for onboard measurements and land-based laboratory analyses (see fluid sampling). Additionally 1 litre of water samples were degassed by using ultrasonic-vacuum degassing technique (Schmitt et al, 1991). The released gas was stored in pre-evacuated glass vials for gas chromatographic and mass spectrometric measurements.

6.4 First results

In total 73 fluid/water samples and 79 gas samples were recovered during the SO-192/2 campaign. All measured data, sample location descriptions, and volumes of sub-samples are summarised in Tables 1 and 2 in Appendix 7.

A revisit of hydrothermal vent fields in the Bay of Plenty showed that hydrothermal venting is still active in 2007. Bubble formation (free gas), and hydrothermal brine outflows indicated subsurface boiling as it was concluded from up to 200°C hot vent fluids sampled in 1998 during the SO-135/Jago cruise. Unfortunately the temperature probe of ROPOS was not working during the Calypso Vent dives. Mixtures of seawater and hydrothermal fluids showed slightly acidic pH-values (~6.4) with a high alkalinity of 3.4 mmol/l, probably indicating near surface carbonate dissolution by hydrothermal fluids.

Low temperature (10-42°C) vent fluids were sampled at the Monowai volcano in two vent fields. The alkalinity and pH showed only small and inverse deviation from seawater, which indicates minor contributions of hydrothermal fluids, or effective benthic turnover of hydrothermal fluids (e.g. at Monowai "Mussel Ridge"). The CTD 3 profile recorded at the Monowai caldera showed similar oxygen, temperature, and conductivity patterns like the background station CTD2 (Appendix 7, Fig. 1). A general trend is the 25°C warm, saline, and well mixed surface layer (~60 m thick), separated by a thermocline and halocline from intermediate water masses (Appendix 7, Figs. 1 and 2). The increase of total oxygen from 6 to 6.5 mg/l at about 80 m water depths is coupled with a temperature decrease in intermediate waters (increased oxygen solubility). A gradual decline of temperature and conductivity is shown from intermediate to deep waters (1600 m water depth, Appendix 7, Fig. 1). The maximum of oxygen between 500 and 900 m water depth probably reflects oxygen-rich cold deep water masses in this region (Appendix 7, Fig. 1).

A revisit and focused sampling campaign at Volcano 19 confirmed up to 270°C hot active venting and phase separation like it was observed in 2005. Near end-member fluid conditions are indicated in the 270°C hot fluid by acidic (pH~4.5; low alkalinity ~0.4 mmol/l) fluids containing ~25-60µmol/l Fe^{2+}.

Volcano 1 was also revisited and sampled in detail after the first observation of hydrothermal venting and vigorous gas bubbling at the volcano in 2005 (Stoffers et al. 2005). The observed gas bubbling was less extreme this time but measured fluid temperatures at the Mussel Fiel site (17-64°C) were comparable to 2005. The 150°C hot fluids sampled in 2005 at the tip of Volcano 1 could not be sampled. Cloudy plumes were drifting above the seafloor at Volcano 1 (possibly sulphur precipitation in the water column), and the plumes are indicated by oxygen decrease in bottom waters measured with CTD 8 and 9 above Mussel Ridge and above the so-called "Sulfur Field", respectively (Appendix 7, Fig. 2, Table 2).

7 CHARACTERIZATION AND REACTIVITY OF PUTATIVE BIOGENIC IRON OXIDES

Sean Langley

7.1 Site Descriptions

Volcano 19

The floor of the western caldera and the west flank of the central cone of Volcano 19 are areas of diffuse venting. No shimmering water or bubbling was observed, however some significant temperature anomalies were noted (Table 7.1). Numerous chimney-like structures were visible throughout the sites (Fig. 7.1), however they were extremely unstable, composed of unconsolidated sedimentary material. They were predominantly rust-coloured, with lighter beige-coloured tops. The chimneys in the western caldera measure up to 2 to 3m in height, whereas those along the west flank of the central cone are much shorter, approximately 2 feet high. The beige-coloured material covering the chimneys is dominated by a microbial mat. Previous investigations have shown filamentous bacteria (similar to the iron-oxidizing genus *Leptothrix*) within the mat community. It is possible that the bacteria are, at least in part, responsible for forming the chimney-like structures and providing some stability to the otherwise flocculent, sedimentary material.

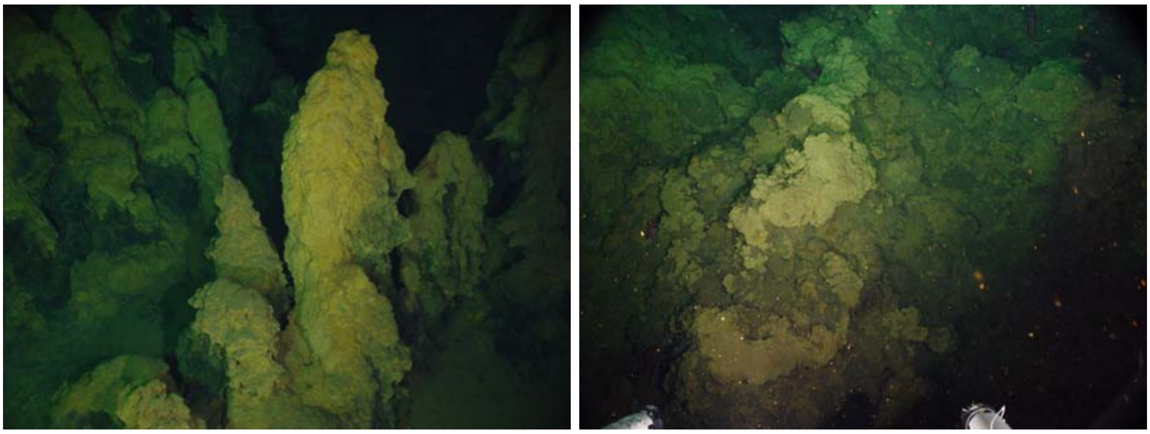


Fig. 7.1: Iron oxide “chimneys” at volcano 19. Left: Floor of western caldera. Right: Western flank of central cone

Volcano 1

At this site, just outside of the third crater, there was extensive deposition of iron oxide/microbial mat material on the sediment surface (Fig. 7.2). The mat material was approximately the same rust colour as that seen in the Western caldera of Volcano 19, however no chimney structures were present. Immediately below the rust-coloured surface layer, the iron oxides were a much darker, red-brown colour. There were no obvious signs of venting such as shimmering water or bubbles; however subtle temperature anomalies were noted (Table 7.1). This site may represent an area where active venting has slowed or ceased, likely affecting both the microbial community structure and processes of iron oxide formation and diagenesis.

Fig. 7.2: Occurrence of iron oxide sediments and cemented ash near the third crater at the Mussel Ridge vent field, Volcano 1.

7.2 Sample Retrieval and Analyses

Suction sampling of chimney material at Volcano 19 was initiated at the tops of the chimneys, in an attempt to retrieve as much of the live microbial biomass as possible. Temperature readings were obtained as the suction sampler penetrated the chimney. The samples consisted of well-dispersed, fine-grained particles, with little clumping of the solid material, and slow settling of the particles from suspension. The colour of the iron oxide phase was a yellow-rust, suggestive of ferrihydrite, or possibly micro-crystalline goethite. Both of these minerals are consistent with those produced by known iron-oxidizing bacteria.

Suction sampling of the sediments at Volcano 1 focused on the first 5 to 10 cm of sediment, and temperature readings were obtained as the suction sampler penetrated the sediment surface. These samples were composed of a deep red iron oxide, suggestive of recrystallization from ferrihydrite/goethite to, perhaps, hematite. Mixed with the iron oxides were larger (5 cm) clumps of a dark-grey to black, brittle material, likely cemented ash. The iron oxides at this site were coarser grained and tended to clump and settle from suspension much more readily than those obtained from Volcano 19.

Sub-samples were analyzed on board for pH and dissolved Fe(II) concentration (Table 7.1). Additional sub-samples were treated or preserved on board as follows: 5 mL fixed in 2% (aq) glutaraldehyde for future analysis by electron microscopy, 25 mL acidified for future elemental analysis by ICP-OES/MS, and 30 mL frozen for future microbial community analysis.

The remainder of the samples were left untreated and stored (refrigerated and aerated) for return to the laboratory in Ottawa, where a sub-sample of each will be freeze-dried and powdered for analysis by XRD, followed by digestion and elemental analysis by ICP-OES/MS. The remaining wet material will be gamma irradiated to destroy any remaining microbial activity. The sterile material will then be used in studies of the microbial reduction, dissolution and recrystallization of biogenic iron oxides (BIOS) by known iron-reducing bacteria. Such studies are important for understanding iron cycling and diagenesis in natural environments. While several studies are currently underway using freshwater BIOS, this will be the first such study examining a (putative) marine BIOS.

Table 7.1: Sample site descriptions for putative biogenic iron oxides at Volcano 19 and Volcano 1.

Dive No.	Sample No.	Volc.	Latitude	Longitude	Depth (m)	Ambient T (˚C)	Sed. T (˚C)	[Fe(II)] (ppm)	pH
R1046	0001	19	24º, 48.2820' S	177º, 1.1412' W	992.1	2.6	16	0.32	N/A
R1046	0002	19	24º, 48.2814' S	177º, 1.1394' W	992.5	2.6	16	0.25	N/A
R1046	0003	19	24º, 48.2664' S	177º, 1.1874' W	1000.2	2.8	39	0.12	N/A
R1046	0009	19	24º, 48.2712' S	177º, 1.1352' W	986.6	5.2	25	0.47	6.10
R1048	0017	19	24º, 48.3528' S	177º, 0.1644' W	503	6.9	42	0.09	6.63
R1051	0009	1	21º, 9.2034' S	175º, 44.7600' W	197.8	19	23	0.02	7.25
R1053	0015	1	21º, 9.2046' S	175º, 44.7636' W	197.0	16	17.2	0.11	7.50
R1053	0016	1	21º, 9.2052' S	175º, 44.7642' W	197.0	16	21	N/A	N/A
R1053	0017	1	21º, 9.2052' S	175º, 44.7636' W	197.0	16	17.4	N/A	N/A

8 BIOLOGICAL INVESTIGATIONS

Di Tracey, Kim Juniper, Anna Metaxas, Catherine Stevens

8.1 Introduction

R/V Sonne Cruise SO-192 (Mango) expedition to the Tonga-Kermadec Arc was a German-Canadian collaboration investigating the geochemical and biological characteristics of active submarine volcanoes along the Tonga-Kermadec Arc. The Canadian ROV, ROPOS, explored and sampled hydrothermal vents, seafloor mineralisation, biological fauna, and recent volcanic formations. The focus was on exploration of previously unmapped volcanic centres over a range of depths from 1500 to <100 m. New Zealand scientific representatives from NIWA and GNS were invited to participate on the cruise. Di Tracey was the NIWA representative on board with funding for her participation provided by the New Zealand Foundation for Research Science and Technology (FRST) Project C01X0508 and the Census of Marine Life field program CenSeam (a global census of marine life on seamounts), Project

UCSO53O1. This report describes the collection and cataloguing of biological samples carried out during the voyage. Once formal identification of the organisms takes place at NIWA, the faunal lists will enable a description of vent and seamount communities and will contribute toward a biodiversity inventory for the region.

8.2 Objectives

The objectives of the NIWA/Census of Marine Life (**COML**; Di Tracey) project include:

1. The description of vent and seamount communities as well as 'background' non-seamount assemblages
2. Compilation of the biodiversity inventory of the various fauna encountered.
3. Sample collection of representative benthic fauna from all sample sites for identification, genetics, DNA bar coding project (fish).

The projects of the Canadian biologists include:

1. Kim Juniper (University of Victoria) with Catherine Stevens (University of Victoria and NIWA)

a) Food web structure in relation to vent habitat stability. Sampling of whole communities at selected locations for stable isotope and lipid biomarker analysis. Emphasis on gastropod assemblages.

b) Contribution of Type 1 and Type 2 Ribulose biphosphate carboxlyase (Rubisco) to chemosynthetic carbon fixation at hydrothermal vents.

c) Sampling of microbial mats, organic detritus and associated fauna at intense diffuse flow vents and within mussel beds (Monowai and Volcano 1).

d) Sampling of sediments and hard surface biofilms in flatfish habitats (Monowai and Volcano1).

e) Measurements of concentration of suspended particles over vents with high volume pump and GF/F filters.

2. Anna Metaxas (Dalhousie University)

a) Reproduction, larval colonization and larval life history of vent fauna. Suction sampling of substratum for eggs and larvae. Net tows during long ROPOS transects to collect larvae.

b) General observations of community composition and species distribution to support above.

3. John Dower (University of Victoria)

a) Flatfish ecology and biology at island arc vents. Continuation of study begun in Mariana Arc in 2004 and 2006. Sampling of flatfish at Monowai and Volcano 1 and any other locations where they are present, for on-going graduate student thesis.

4. Verena Tunnicliffe (University of Victoria)

a) Mussel shell growth and dissolution under acidic conditions. Sampling of 10 live mussels and a few dead shells from each of Monowai and Volcano 1, plus water samples from each mussel bed.

b) Faunal turnover along volcanic arcs. Sampling of gastropod populations and mussel bed infauna at Monowai and Volcano 1 and opportunistically at other locations.

8.3 Methods

Study Areas

The main survey area comprised features within the Kermadec and Tonga Arcs. The features surveyed were the Calypso Vents, Bay of Plenty, Monowai Seamount, Volcano U, Volcano 19, Hine Hina Vents (Lau Basin), and Volcano 1.

Vessel gear and scientific equipment

RV *Sonne* is a 98 m multi-purpose German research vessel. On board equipment includes a hull-mounted swath mapping system, ELAC paper echosounder (LAZ 4400), grab with video camera (TVG), CTD and Rosette, and a greased volcanic rock corer (VRC). The ROV system was the Canadian ROPOS submersible. ROPOS is equipped with several features including still and video camera systems, manipulator arm, and suction sampler.

Biological sampling methods and treatment

Swath mapping was carried out over and adjacent to all features. ROPOS was the main sampling tool and along with collecting biological samples, collected still and video footage, geological material, gas, water, and sediment samples. An echosounder survey using the ELAC sounder was carried out at Calypso Vents to search out gas bubbles. At all sites the TVG collected video footage, geological and biological samples, and the CTD-rosette was deployed to collect water samples and temperature and salinity data. The sediment corer VRC sampled very small volumes of bottom sediment at some sites.

During ROPOS dives, fish and invertebrates were identified visually to main taxonomic group or where possible, to species. Organisms collected at each station by ROPOS and TVG were catalogued and kept for the NIWA collection to enable identification to species (or the lowest possible taxon). Sample processing involved grouping of the organisms by taxon and then allocating to each organism or to several of the same organism, a unique number, a voyage and NIWA station code, name, and species code. Counts were made, weights estimated, and the organism(s), or a sub-sample, were fixed in either alcohol or formalin, or frozen. Data were entered into a Microsoft access database.

Data recording

<u>Station data:</u>

Categories	R for ROPOS, G for TVG grab sample number, F for baited fish trap
Areas	BPLE Bay of Plenty; MONO Monowai Seamount; VOU Volcano U; V019 Volcano 19; LAUB Lau Basin Hine Hina site; VOO1, Volcano 1.
Strata	CALY for ROPOS dive tracks covering Calypso Vents area (stations 4 & 5)
	CALS for vent site 4 in southern region (also area of vents 1-8)
	CALN for vent site 9 in northern region (also area of vent 10)
	MONO for ROPOS dive tracks covering Monowai Seamount (station 10)
	MOCO for the Caldera site
	MONM for mussel ridge
	MONC for main cone in south
	V19 for Volcano 19
	V1 for Volcano 1
	VOU for Volcano U
	HINE for Hine Hina site

Station code- -dive no 1039, 1040, etc for ROPOS, or 4, 5, 8, etc for TVG.

8.4 Survey Schedule

Date (Time of gear deployment in GMT)

26 April	Departed Auckland 0900 h. Science meeting and safety briefing. Arrived early evening at **Calypso Vent** sites, Bay of Plenty. Bathymetry survey using swathe system carried out and ELAC echosounder was run to note the location of CO2 bubbles.
27 - 28 April	ROPOS dives 1 (R1039) and 2 (R1040) sampled southern, south eastern Calypso vents, (1-8) and northern Calypso vents (9 and 10). Rock, sediment, water, biological, and gas samples collected. Biological samples collected by ROPOS at site 4 and by TVG at sites 4 and 9. CTD casts in region of north and south sites. Swath mapping overnight.

29 - 30 April	Steaming to Monowai Seamount. Science meetings, weekly report preparation, station and biological summary data.
1 May	Arrive **Monowai** Seamount 18.00 h. CTD cast completed SE of cone, vessel moved to cone area, but after at least 2 explosions were felt, moved away from the region. Volcanic activity producing gas effervescence, bubbles at surface, then green water coloration. Carried out core sampling on smaller cones in region, and swathe mapping SE of cone.
2 May	ROPOS surveying base of cone. Dive R1041. Depth 400 m, visibility poor, turbulence and detritus in water, as well as microbial fluff. Occasional dense cloudy particles, evidence of explosions, bombs on seafloor. Bubbles and subsequent green coloration at surface. 2nd ROPOS dive R1042 following a track running up caldera wall from 1700 m to 800 m. Bottom of caldera smooth fiat, 2 species of prawns, one with long filamentous feelers, *Syanophobranchus* grey cutthroat eel, small rattails observed. Patches of sediment covered talus. White bulbous sponges at about 1100 m, growing on basaltic lava. Prawns in water column. Large flat lava pillows, steep slopes and soft sediment visible, some? gorgonians and hydroids. At 840 m community changes, seeing stylasterids, glass sponges, stalked crinoids, fan corals, sea pens. ROPOS on board at 1400 h. 2 TVG grabs (TVG19, 20) carried out.
3 May	3 TVG grabs (TVG21, 22, 23). Vent fauna at TVG22. ROPOS in water but some faults. Mussel Ridge dive at Caldera deployed, R1043. Sampled *Pisces* vent site. Zoarcidae (eel pout), 2 crab species (Lithodid, *Paralomis* spp.). Crabs feeding on beds of bathymodiolid mussels, mussels and worms on bacterial mat. *Amphisamytha galapagensis* (tube worms) and occasional gastropod observed. Various vent site temperatures measured (ranged from 18 to 42 deg C). Plankton sampling above mussel ridge. Biological sampling on ridge obtained 400 kg of mussels. 2 grab samples. TVG26 obtained large Bathymodiolid mussel sample, crabs and very high numbers of *Lamellibrachia* spp. tube worms on rocks – various sizes.
4 May	TVG grab sampling continued at Monowai (TVG28-30). Fauna in TVG – some cup corals, bryozoans, sea stars, ophiuroids, bivalves. Dive R1044 deployed on Bouquet Vent adjacent to Mussel Ridge. Suction and grab samples — collected small amount of vent fauna, 4 mussels, anemones, few shrimps, *Lamellibrachla* spp., scale worms, bacterial mat, and *Amphisamytha galapagensis.* Also collected plankton samples. Dive R1045 on **Volcano U,** 2 hours steam from Monowai. Very steep slope, often vertical, alternating with some 45° slope. Recorded volcaniclastics and dikes. Collected rocks and possible tube worm material. CTD cast made. Steaming to Volcano 19.
5 - 9 May	Three ROPOS dives (R1046, R1047, R1048), and TVGs carried out at **Volcano 19**. Volcano comprises a western caldera, central cone complex, and an outer caldera rim. Large Fe oxide and anhydrite chimneys surveyed and sampled. Observed and sampled several lucinid clams, fiat fish seen in sediment at base as weil as on chimney wall, *Scierasterias* sea stars, polychaetes, gastropods, and a few pieces of dead bathymodiolid shell. More fish observed at this volcano including a small Epigonidae, *Beryx* spp., large deepsea angler fish, Centrolophidae. Weather deteriorated. Two days of mapping area but no sampling carried out. Late on the 9th departed for Lau Basin.
10 May	Arrived **Lau Basin.** Weather greatly improved, large swell. Chinese research vessel in region. CTD carried out then one ROPOS dive carried out in the Hine

	Hina vent area, R1049. What appears to be two species of *Bathymodiolis* spp. collected, one of which was a very large pale shelled spp. and each animal had at least one commensal scaleworm.
11-15 May	Five ROPOS dives and 11 TVGs sampled **Volcano 1.** The post caldera scoria vent sites were surveyed and sampled for biological material. Sample areas included a sulphur site and two shallow cones where organisms were living in both a photosynthetic and chemosynthetic environment. A large number of diverse biological organisms were collected and included several samples of *Bathymodiolus* spp. and over 40 flatfish *(Symphurus* spp.) caught in baited fish traps.
15-17 May	Transit to Suva, Fiji

8.5 Results

Station data from which biological data were collected by ROPOS and TVG are summarised in Appendix 6. *Sonne* station numbers can be matched to the NIWA station numbers; in addition, NIWA allocated station numbers to each site sampled during each ROPOS dive. The Appendix 8 lists the biological fauna sampled by sample method for each of the survey areas with Figures showing some images of the various fauna sampled during the cruise. Sequential NIWA station numbers were given to the ROPOS and TVG biological samples. Station data for all gear deployments *(Sonne* log) and all sample station data for ROPOS (e.g. biological as well as water and rock sample sites) are available on CD.

Calypso Vents

At the Calypso sites, Bay of Plenty, stations 1 and 5 were the ROPOS dive track, stations 2, 6, 7, (manipulator arm) and 8 (suction) were ROPOS sample sites. Stations 3, 4, and 9 were TVG grab sites. All ROPOS biological sample stations were in the southern vent area, vent 4, and the TVG sample stations were in both the northern and southern vent areas. TVG4 was at vent 4 and TVG5 and TVG8 were at vent 9 in the north. A total of 214 organisms were collected, 38 by ROPOS, and 176 by TVG. Large numbers of the thalassinid reptant were sampled at vent 9 from a 500 kg grab sample of soft ash sediment. Also sampled at vent 9 were marine worms taken from anhydrite precipitate. Bathymodiolid mussels *(?Gigantidas gladlus)* were sampled primarily from vent 4 but one specimen was taken by grab in the north. We are yet to confirm that the very small specimens of vent mussels collected during the biological sampling are a juvenile form of Bathymodiolid mussels or another bivalve species. The red/orange anemone and the white finger sponge were abundant in both areas but only sampled from the south vent site. The possible faunal difference between northern vent 9 and southern vent 4 was more likely due to bottom type than the particular vent environment. However mercury related mineralisation was occurring at vent 9 in the northern region, and it was in this area that the large numbers of the thalassinid reptant were sampled. Distribution patterns of fauna by bottom type from ROPOS observations are yet to be described but it was noted that the red/orange anemone increased in density dose to the vents.

Monowai Seamount

This seamount comprises a 10 km wide active volcano and **a** very large caldera (Figure 4). Mussel Ridge, on the western side of the Caldera, is where active hydrothermal vents are present. Stations 10, 11, 17 and 25 were the ROPOS dive track. Biological samples were collected from 5 ROPOS and 10 TVG sites. ROPOS biological sample stations were focussed on the Mussel Ridge region and the TVG sample stations covered the ridge as well as additional sites in the caldera e.g. at the 'Bouquet Vent' site. Biological species in this region was reasonably diverse. Key fauna were the vent mussel *Bathymodiolus* sp. *(?brevior)* and the tube worm *Lamellibrachla* spp. The total number of organisms recorded from ROPOS dives 1043 and 1044 numbered 297. TVG grabs produced 628 individual specimen samples.

Volcano U

Station 27 was the ROPOS dive track. A sample that was possibly tubeworm material was collected, but in general this volcano appeared devoid of macrofauna.

Volcano 19

This site contains two craters and several cones. Stations 28 and 34 were the ROPOS dive tracks, stations 29 to 43 were ROPOS biological sample sites. A total of 268 organisms were sampled using ROPOS and these included several unidentified clams as well as a lucinid (possibly *Bathyaustriella thionipta).* Numerous *Scierasterias* spp. sea stars and unidentified crab species were also sampled. Stations 30-33 and 44 were TVG grab sites. A total of 5 thalassinid reptants and a lithodid crab were sampled by the TVG. Most ROPOS biological sample stations were in the Central Cone complex. One baited fish trap was deployed at the beginning of the dive and on retrieval had captured three *Scierasterias* spp. sea stars but no fish.

Lau Basin

Stations 46 to 49 were the ROPOS dive tracks and sample sites covering the deep (1832-1887m) Hine Hina vent sites at Lau Basin. ROPOS biological sample stations were carried out at 'Mussel Patch' and there were 2 TVG grabs in the region. Fauna comprised two species of *Bathymodiolus* vent mussels, a large limpet species, and squat lobsters.

Volcano 1

Volcano 1 comprises two stratovolcanoes with summit calderas and a series of small cones and ridges. The northern region of Volcano 1 was intensively surveyed; stations 50, 57, 64, 66, and 74 were the ROPOS dive track stations. Sampling stations were carried out along these dive tracks at named sites including Mussel Vent, Sulphur, Super Cool, Bubble's Vent, and Barracuda. 11 TVG stations were carried out at various sites and several of these obtained biological samples. Fauna included high concentrations of bathymodiolid vent mussels along with small crabs and gastropods, and the flatfish *Symphurus* spp (Fig. 8.1).

Fig. 8.1: Image of a 5 cm *Symphurus* spp, sampled at the post-caldera chain of craters, Volcano 1).

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