ENVIRONMENTAL ASPECTS OF WEAPONS TESTING AT MORUROA ATOLL, SOUTH PACIFIC.

Paul Johnston, Ruth Stringer, Dave Santillo & Angela Stephenson,
Greenpeace Research Laboratories,
University of Exeter,
North Park Road,
Exeter EX4 4QE,
UK

Greenpeace Research Laboratories Technical Note 04/96
July 31, 1995

SUMMARY

The test site used by the French at Moruroa Atoll in the South Pacific consists of an extinct volcano overlaid by limestones and dolomites laid down by corals. In addition to atmospheric and safety tests which left the lagoon contaminated with up to 20kg of plutonium, 123 underground tests have been carried out resulting in a substantial inventory of radioactivity remaining underground.

There have long been concerns about the structural integrity of the reef system, yet virtually no data have been released into the public domain. Nor have scientific expeditions been afforded enough time comprehensively to evaluate the problem.

Modelling exercises have shown that there is potential for radionuclides to enter the wider environment through the hydrological processes taking place in the Atoll structure.

This circulation and escape is likely to be facilitated by the fissuring and fracturing caused by the tests themselves. Considerable damage has been done to the structure of the atoll, including the displacement of portions of the protective upper limestone apron and subsidence of the upper layers.

Escapes of short-lived radionuclides have been detected after two tests monitored by expeditions of independent scientists in 1983 and 1987 respectively. These were attributed to an exceptional accident during valve decoupling whilst obtaining samples from the blast cavern. This is, however, also evidence of direct connection between the cavern and the upper, porous layers of the geological structure. In addition, elevated levels of plutonium isotopes have been found in oceanic waters in the vicinity of the test site.

Although limited, this evidence outlines the necessity for a comprehensive evaluation of the Atoll and its environs prior to the resumption of any testing programme.

INTRODUCTION

Between 1966 and 1991, 175 nuclear test explosions were carried out at Moruroa and Fangataufa Atolls as part of the French nuclear weapons testing programme. Both of these atolls are part of the Tuamotu Archipelago located in French Polynesia. Of the 175 tests, 44 were atmospheric and took place on the two atolls between 1966 and 1974. After this tests were conducted underground at the rate of between four and eleven tests per year. Of these 8 were conducted at Fangataufa and the remaining 123 at Moruroa. The yields of these explosions have never been officially released by the French Authorities, but are estimated on the basis of New Zealand and Swedish seismic studies to be around 2500 kilotons TNT equivalent. There is some discrepancy in the numbers of tests reported by different authorities since some may not have been reported by the French.

The tests are conducted by boring a shaft into the basalt rocks which form the base of the atoll structure, and lowering the device together with testing equipment into the borehole. After backfilling with drilling debris, the device is detonated. Subsequently, a second shaft is opened into the cavity formed by the explosion to supplement measurements made in the first few milliseconds of the explosion.

The shafts drilled range in depths from 500-1200 metres into the basalt core. Initially, shafts were drilled into the outer rim of the lagoon, but since 1981 higher yield tests were shifted to shafts drilled under the central lagoon. In 1986 all testing activity was shifted to the central zone.

The flow of information concerning the outcomes of these tests in all respects has been tightly controlled by the French establishment. There have been very few opportunities for independent scientists to scrutinise operations or to conduct surveys of the area in question. Although four surveys have been allowed by scientific researchers independent of the French military, these have been highly restricted. Periods of three to five days have been allowed and activities restricted to certain sample types and tightly specified areas of the lagoon.

There is no doubt that any evaluation of the impacts of the underground tests is confounded by the residues of radioactive materials remaining from the atmospheric testing. Certain of the above ground tests were "safety tests". As a result of these tests together with accidents and the storage of radioactively contaminated artifacts in a 30,000 square metre area on the North Coast of the Atoll, around 20 kg of plutonium-239 are now thought to be present in the sediments of the lagoon itself. This is estimated to result in the transfer of around 20 Gigabecquerels of Pu-239 into oceanic waters annually [1].

Inevitably, concerns have been raised about the possibility of the radionuclides produced in the underground tests reaching the environment. The effects of the testing programme on the structure of the reef system are an area of particular concern. These concerns have been heightened by the reporting of the results of the Atkinson and Cousteau Foundation visits in 1983 and 1987 respectively. The possibility that further tests may be conducted by the French authorities commencing in September 1995 is taking place against a background of an informational vacuum. These notes, therefore, outline the concerns in relation to the environmental safety of the proposed tests, in turn a function both of lack of information available for independent scrutiny and the limited data available on the structure and integrity of the reef. The limited source references from which such information can been drawn are given. Discussion is limited to Moruroa Atoll, since the best quality information is limited to this site.

It must be emphasised that the French authorities will have conducted a large number of measurements on the tests and upon the lagoon itself. To date very few of these data have been published. According to reference [5], the Service Mixte de Securite Radiologique in France established a monitoring network consisting of 50 sampling stations which were sampled at the surface and near the bottom of the lagoon from 1979 until 1986. These data have not been presented for independent scrutiny. In June 1990, 18 samples of 1000l of seawater were collected from sites within the lagoon by the SMSR following the Cousteau expedition. Some samples have been subject to intercalibration exercises under the auspices of the IAEA [6 & 7]. It is not known what other environmental matrices have been monitored, nor what the results of any such monitoring revealed. Currently, 10 monitoring stations appear to be in use, covering the whole lagoon [5].

OVERVIEW

The Moruroa test site has not been subject to any thorough assessment by independent scientists for environmental impacts resulting from testing. The limited surveys conducted in 1983 and 1987 took place over a period of three to five days with limited access to the site. Monitoring data collected by the French Authorities has not been formally published or made available for independent scrutiny. No official figure has been published for the yield of the devices tested and these have been estimated from New Zealand and Swedish seismic data. There is, therefore, a need:

1) to release data on the type and yield of the devices tested together with the inventory of radionuclides likely to have been formed;

2) to carry out an independent evaluation of monitoring data and examination of the protocols used;

3) to carry out an independent evaluation of the current condition of the test site.

POINT

There has been no robust environmental assessment carried out at the Moruroa test site. Few of the data presumably gathered by the

French Authorities have been made available for independent scrutiny.

DESCRIPTION OF SITE

There is some information available about the structure of Moruroa Atoll which has been published in the open scientific literature. Some of this is presented in Refs [2 & 3]. Essentially, the island is of volcanic origin, modified by the activities of reef building organisms. It is 25 Kilometres long across the east-west axis and 9 kilometres at the widest point on the north-south axis. An opening through the reef, about 5 kilometres wide, gives access to the lagoon on the north-west coast of the atoll. The crown of the reef is around 65km in extent.

Boreholes drilled into the atoll have shown a layered structure typical of other atolls. The Moruroa structure is relatively well investigated in relation to other reefs and the results from five drillings have been reproduced in reference [3]. The depths of the various layers making up the structure are not uniform throughout and consist of:

1) A top layer of limestone extending to a depth of between 130-200m in depth.

2) A layer of dolomite extending to between 260 and 420m in depth.

3) A transition zone of montmorillonitic and kaolinitic clays overlain by calcareous rocks extending to between 350 and 450m in depth.

4) Underlying the transition layer is a layer derived from aerial volcanic activity extending to about 550m

5) A basalt layer produced by submarine volcanic activity extending to the depth of the boreholes drilled.

In essence this structure has developed since the cessation of volcanic activity 8-9 million years ago. The reef building activity has taken place as the island structure has gradually sunk below sea level. Hence the geology also varies depending upon the relative times that the base materials became submerged.

Hence, the structure is heteroogenous and the layers that comprise it are also heterogenous. The picture is also complicated by periods when sea-levels fell and the limestone strata were eroded to produce large dissolution cavities and faults. Given the complex nature of the geological structures it is not possible to derive a general model of the internal geology nor of the hydrology. Water movements and circulation within the structure are inevitable. The porosity coefficient ranges between 10-30% in the various levels of the coral platform.

The zone of aerial volcanism also contains material with a high porosity ranging from 6-30%. This is due to the heterogeneity of its composite materials. Finally, the zone of materials produced by submarine volcanic activity are fissured and splintered with complex dykes cut vertically into the structure. The porosity of this is estimated as having a coefficient of 6%.

Significantly, Reference [8] notes that the variation in the thickness and the composition of the transition zone casts doubt upon its ability to act either as a barrier to the migration of radionuclides formed in the weapons tests, or to cushion and channel the seismic energy due to the nuclear explosion.

Studies of water movements through the structure of the lagoon have shown rapid lateral exchanges between the sea water and the water held in the interstices of the rock. Vertical migration has been set at 90m per year in the first 450m of this structure based upon empirical data [see: 3]. A useful overview of the hydrology of the Atoll was produced in 1986 by New Zealand workers [4]. This led them to conclude that in its natural state the Atoll is as "leaky as a sieve". Moreover, they also point out that the thermal energy from nuclear detonations will also force circulation patterns tending to accelerate the movement of radionuclides upwards. On the further assumption that the nuclear tests had produced considerable fracturing of the atoll structure, the conclusion reached was that radionuclides generated by the tests could begin to leak into the lagoon within 10-100 years. The porous nature of the dolomite layer would encourage the flow of seawater through the structure into the lagoon. This, itself is flushed by water movements, and an estimated flux of 100 million cubic metres of water through the opening in the reef crown takes place daily.

Atoll water relationships are known to be hugely complex from studies on other atolls [2]. Water circulation through the ghighly porous structure has been highlighted by work on other reef systems [12] while information on the high porosity of Moruroa, indicating many fractures within the basement is provided in Reference [13].

OVERVIEW

The structure of the atoll is geologically complex consisting of various strata all of which are porous to some degree. Even if it is assumed that no fracturing has taken place as a result of the testing, the natural porosity of the rock is conducive to water movement and hence to the mobilisation of radionuclides which can be introduced into it. There is a need, therefore, to establish:

1) A comprehensive evaluation of the hydrology of the reef system.

2) Empirical determination of radionuclide movements through the porous strata.

Movement of water through the structure of the Atoll will also be affected by any fracturing of the structure due to the tests themselves which could markedly affect the movement of materials through the structure by considerably increasing the porosity. In reference [3] it is noted that the cavity, fractures and interstices should fill with interstitial water after a few days, a point also made in References [4 & 9], since they are below and are themselves in a water saturated zone.

POINT

The Atoll is composed of several varied layers of geological material. None of these layers are themselves homogeneous. The limestone layers have a high porosity and both the porosity of these layers and the underlying volcanic strata will be increased by fissuring. The transition layer does not appear to be a barrier to the migration of radionuclides from the test chambers.

EVIDENCE OF FRACTURING AND DAMAGE TO THE ATOLL.

The detonation of a nuclear device in the basaltic rocks produces temperatures of 100,000 degrees Celsius and gas pressures of around 1Mbar. This causes rocks in the immediate vicinity to vaporise, and those further away to melt. The end result is to produce a cavity whose size is dependent upon the yield of the device. Rocks around the cavity will be fractured by the blast and the roof of the cavity collapses to create a "chimney" [9]. The subsidence chimney is heaped with very coarse elements [Ref 3] with large spaces between them. As an example, based upon US data, with a 50kt yield, a cavity of 37 metres radius, with a chimney height of 148m will be formed. The fracture zone radius is likely to be 266m in radius (Ref 3].

Damage to the limestone layer is particularly well documented, that to the volcanic layers less so. Fracturing and damage to the structure of the Atoll was first reported by the 1983 Atkinson expedition [8]. They noted that the structure of the limestone forming the upper part of the atoll was altered by fissuring subsidence and underwater slides. Moreover, they stated that the volcanic rocks in which the blasts have taken place must have been severely modified in the zones surrounding the cavities formed.

The full impacts appear to be severe. Reference [8] reports subsidences of over a metre in areas of the Atoll affected by testing. As pointed out in Reference [1], fissures are propagated by testing, a result of cumulative compacting of the limestone. This will serve to increase the lateral and vertical water transport in the carbonate areas of the Atoll. The scope and scale of the problem are not known. No data have been placed in the public domain for independent scrutiny concerning the depth and relative positioning of the test shafts. It is, therefore not known, to what extent the various fracture zones may have interacted with each other, and to what extent the integrity of the reef as a whole is compromised. The lack of data, and the impossibility of evaluating the integrity of the volcanic rocks was the subject of numerous remarks in Reference [8]. The methods of siting the shots as given in Reference [3]. The siting is calculated such that the thickness of the sound volcanic rock is equal to twice the radius of the cavity produced. This needs clarification.

Reference [3] notes that observations were made on SCUBA and submarine dives to 50 and 230m respectively. These took place on the external slope of the Atoll in Zone "Zoe" in the South of the Atoll. This area had been the location of a large slide of the external submerged part of the Atoll following the detonation of a 120kt device which became stuck in the shaft in the limestone. The slide mobilised around a million cubic metres of rock, creating a tsunami like tidal wave. Internally in the Atoll, Taken together, Reference [4] considers that these events must have been accompanied by deep fracturing. Reference [1] suggests that a cavern 140m in diameter was formed. On the basis of the formulae presented in reference [3] this implies a fracture zone almost a kilometre in radius. This would extend to the periphery of the reef and to the surface. Observations during the diving programme found that both new and old fissures were apparent, and that there was evidence that at the time of observation, recent rock falls and cracks of recent origin were present, showing that tests under the lagoon, rather than at the periphery of the reef were capable of causing disintegration of the limestone crown and had been doing so. Report [8] noted that slippage of the outermost limestone apron layer would effectively strip the Atoll of its water protective skin.

Both Reports [3 & 8] draw attention to the possible poor condition of the volcanic rocks surrounding the chambers but note that it was not possible to observe this directly. Both note that fracture zone overlap may have occurred. This creates the possibility that the test chambers could be directly exposed to moving water as well as weakening the atoll structure.

The potential role of the secondary sampling bore made after the explosion is considered below.

OVERVIEW

The nuclear tests can be expected to have caused widespread fissuring and fracturing of the base rock and the limestone overlay. Both the Atkinson and the Cousteau report document extensive damage to the Atoll structure, although both note that while damage to the volcanic rocks may be serious it can only be inferred. In places, the outer limestone layers have slipped and will have increased the permeability of the atoll and exposed it to erosive action by the sea. In other areas, the limestone has subsided by over a metre. Fissuring will increase the overall permeability of the reef and also facilitate the escape of radionuclides from the cavities produced by the tests.

POINT

Evidence exists of extensive cracking and fissuring of the reef which will increase the likelihood of radionuclides from tests entering the wider environment.

EVIDENCE OF RADIOACTIVE ESCAPES

The detonation of a nuclear device results in the emission of radionuclides with a variety of properties. Some such as tritium and isotopes of iodine are relatively volatile, Others, such as caesium isotopes are soluble. Other isotopes will be incorporated into the vitrified rock formed on cooling after the explosion. Although this is a glassy substance, it will be cracked and subject to leaching at an unknown rate. Reference 3 states that the average activity of the reformed rocks is around 1.3 microcuries per gram. The precise radioactive inventory will depend upon the yield and the type of the device. As an approximation, Reference [3] suggests that the activities of Strontium-90 and of Caesium-137 produced in the detonations are 260,000 and 650,000 Curies respectively.

There are several anomalous findings of radioactivity in the Atoll environment. Some of these have been subsequently confirmed by the French Authorities although the release of I-131 and Cs-136 was admitted only after what was described as a very unusual incident involving the decoupling of valves at the head of the test shaft.

Despite the limited time and logistic resources available to both the Atkinson and Cousteau expeditions, both found evidence of radioactive leakage. The Atkinson group were authorised by the French Authorities to conduct a single experiment. They found levels of tritium at 500Bq/cubic metre in the interstitial air of the surface terrain soil as against an expected concentration of 0.2 Bq/cubic metre. Two explanations were furnished in the report [8]; either venting of gaseous tritium from underground cavities or a faster groundwater flow rate than admitted. It was noted that "volatile and gaseous fission products migrate from the explosion cavity at the moment of the test". The quantities were such that this was not thought to be due to incomplete sealing of the shaft. Tritium is a highly mobile radioactive element. Subsequent tests by the French Authorities according to the Cousteau team were not able to confirm the result [3]. Tritium and Krypton isotopes are now apparently monitored routinely, subsequent to the 1982 expedition by Haroun Tazieff [3].

Two anomalous results were recorded by the Cousteau team in the aftermath of the test that they witnessed. The very short half-life isotope Iodine-131 (8 days) was detected in all the sediment samples shortly after a test. In addition the same isotope was found in a sample of zooplankton from the lagoon. Although not explicitly mentioned in Report [3], Report [1] notes that the highest concentration was found in the sample of sediment farthest from the site. Ultimately, the French explained the phenomenon as the release of water from a secondary borehole to the chamber, drilled for testing purposes. This is clear evidence of venting of radioactive material. The release was admitted as 1.3×10^{5} Bq of Cs-137 and 2.0×10^{11} Bq I-131[5]

The same explanation is offered for traces of Cs-136 (release $1.4x10^6$ Bq) detected by the French Authorities in a follow up to the Cousteau work. Unusually, this was published in an academic journal, one of the few examples of work from the programme appearing thus [5]. The second shaft is an unknown entity. For example, while the primary shaft is lined in some cases [3], it is not known whether this is observed for the secondary shaft opened to collect samples of lava from the test cavern. It does, however, de facto, act as a second, unsealed conduit from the cavern, through the fracture zone and into the limestone layers. It has also been admitted by the Authorities that radioactive elements may be released from them. The French Authorities did not report this incident until the evidence forced them to do so.

The Cousteau study also reported elevated levels of Cs-134 in some of their samples. Cs-134 was in use as a tracer and Report [5] advances contamination of the Cousteau samples as the most likely explanation of the presence of this low yield isotope. Interestingly, the Cs-134 was also accompanied by elevated levels of Cs-137, which in Report [5] published by the French Authorities is a used to point out the similarity with the caesium signature from Chernobyl. Weak activity from Cs-134 was also found in the plankton samples. Intriguingly, moreover, Cs-134 was also found in a survey of plankton, conducted outside the twelve mile limit from the SV Rainbow Warrior [10]. In addition elevated levels of Antimony-125 were detected in one of the samples. This finding is of interest given that Cs-134 should not have been found given its short half-life and its
relatively low yield in weapons detonations. The Cs-137 released is stated to not have been sufficient to raise the Cs-137 levels in the Lagoon above existing levels. The French Authorities have refuted these findings as being due to contamination, possibly from Chernobyl. Buske [11] suggests that iradiation of Portland Cement used in lining the shaft could be a potential source.

Finally, IAEA studies have detected elevated levels of plutonium in seawater samples taken down current of Moruroa and Fangataufa Atolls, outside the twelve mile limit. The most reasonable explanation of this is remobilisation of highly contaminated lagoon sediments, but leaching from test caverns cannot be ruled out.

OVERVIEW

It has been admitted by the French Authorities that there are circumstances in which volatile radioisotopes may be emitted from the cavern resulting from the test. Tritium is a highly mobile element which would be expected to migrate rapidly away from the test cavern through fissures and faults. Hence as expected, the most mobile element is detected first. This is a significant finding, and one which should have been followed up. This appears not to be the case. None of these studies have published data for krypton isotopes. The presence of I-131 and Cs-136 in the vented water, together with Cs-137 indicates that a direct pathway exists through which radioisotopes can be conducted through the entire Atoll structure, including the porous limestone areas. This pathway is in the form of the secondary shaft. Anomalous measurements of Cs-134 found by Cousteau have been strengthened by a seemingly elevated level of Cs-134 in plankton outside the 12 mile limit.

POINT

Radioactivity has been emitted directly from test chambers to the surface, demonstrating the existence of pathways through which migration may occur.

THE NEED FOR A BASELINE STUDY

The major problem concerning the evaluation of the Atoll environment is the absence of data. In contrast to the few days that have been made available to scientific expeditions in the past, there is a need for a comprehensive and integrated scientific programme to be carried out. The basic elements are as follows:

1) A full survey of the topography of the atoll using side scan sonar and a remotely operated vehicle equipped with cameras and testing instruments. This will establish the nature and occurrence of any externally visible fissures. These may be present in the basaltic parent material laid down by aerial and submarine volcanic activity in which tests are conducted, or in the overlying transition zone, dolomite and limestone strata. In turn this will allow an evaluation, supplemented by empirical measurement of actual concentrations of radionuclides, of the potential for release of nuclides from the internal reef structure.

2) A shallow seismic testing programme to establish the degree to which the internal integrity of the atoll structure has been compromised by previous testing. Such a programme would provide some information on the degree of internal fissuring of the parent and overlying materials and also contribute substantially to an evaluation of the potential for radioactive leakage to occur from the atoll structure. Together with data produced from the visual/sonar inspection an evaluation is then possible of the potential for serious structural changes in the atoll produced by future weapons testing.

3) A comprehensive sampling campaign to investigate the concentrations of radionuclides in fish, planktonic organisms, sediments and coralline structures. Where feasible, samples will also be taken from various locations outside the atoll to provide data on existing background levels. This exercise will help to establish whether radioactive materials have been released. It will also give some indications of the quantities of radiation released. By using coralline materials and analysing the radionuclides present in the skeletal matrix, it may be possible to establish the timing and approximate magnitude of releases of radionuclides in the past.

4) An exhaustive determination of the hydrology of the atoll and

reef structure. This should determine the general water movement through the various strata of the atoll. Knowledge of water movements through the system, the interaction between fresh and salt water in the reef system, the presence and size of freshwater lens systems will allow a more precise estimate of the speed at which radionuclides may be carried to the outside environment as a result of failure of these substances to be contained within the reef structure. In particular the hydrological relationships of fissures and faults identified by 1 & 2 above and the remnant test chambers and the boreholes leading to them is a high priority.

5) Following these evaluations, an epidemiological study integrating retrospective and prospective elements should be initiated to assess the local and regional health impacts of the testing regime, past and present.

6) A comparison of the potential for radionuclide release from the testing sites should be made with standards routinely enforced for civil nuclear installations.

This programme of work is a basic minimum that should be carried out even if no further tests were planned. This programme is currently being developed into a more detailed protocol by a group of participating scientists. Should a decision to resume testing be taken after this programme is carried out and its results fully considered, it should be agreed that the programme be repeated immediately after the test series has taken place with appropriate monitoring at the time of the tests themselves.

References

[1] Robbins, A. Makhijani, A. & Yih, K. (19??) Radioactive Heaven and Earth: The Health and Environmental Effects of Nuclear Weapons Testing In, On and BAove the Earth. A report of teh IPPNW Interna-tioanl Commision to Investigate the Health and Environmental Effects of Nuclear Weapons Production and the Institute for Energy and Environmental Research. Publ. Apex Press, New York.

[2] Guilcher, A. (1988) Coral Reef Geomorphology. Publ. Wiley NY 228pp.

[3] Cousteau Foundation (1988) Scientific Mission of the Calypso at the Moruroa Site of Nuclear Testing. Translation by Davis, M.D. of the document published by the Cousteau Foundation, November 1988, 78pp.

[4] Hochstein, M.H. & O'Sullivan, M.J. (1986). The undergound hydrology of Mururoa Atoll. New Zealand Engineering, October 1, 1986, pp.47-49.

[5] Bourlat, Y. & Martin, G. (1992) Precise determination of the concentration of radiocesium in the water of Mururoa Lagoon. J. Environ. Radioactivity.

[6] IAEA (1988) Report on the intercomparison run SD-A-1: Radionuclides in marine sediment IAEA Report No: AL/012, Publ. IAEA, Monaco. December 1988.

[7] Ballestra, S. & Noshkin, V. (1991) Summary of adionuclide intercomparison results in seawater and plankton collecetd outside Mururoa Atoll. IAEA Report No: IAEA/AL/044. Publ. IAEA, Monaco. July 1991

[8] Atkinson, H.R. (1984) Report of a New Zealand, Australia, Papua New Guinea Scientific Mission to Mururoa Atoll. Publ. Ministry Foreign Affairs, New Zealand 166pp.

[9] Hochstein, M.P. & O'Sullivan, M.J. (1988) Geothermal systems created by underground nuclear testing. Proc. International Scientific Symposium on a Nuclear Test Ban, Las Vega, USA.

New Zealand Geothermal Workshop 1985 6pp.

[10] Buske, N. (1991) Radioactivity in Plankton outside the 12-mile exclusion zone of the French nuclear test site. Report of the 1990 Scientific Mission of the Rainbow Warrior. Publ. Greenpeace International, Amsterdam.

[11] Buske, N. (1990) Cesium-134 at Moruroa- Review of the Calypso Samples. Publ. Greenpeace International, Amsterdam.

[12] Rougerie, F., Fagerstrom, J.A. & Andrie, C. (1992) Geothermal upwellin: A solution to the reef nutrient paradox? Cont. Shelf. Res. 12: 785-798.

[13] Rougerie, F. & Wauthy, B. (1993) The endo-upwelling concept: from geothermal convection to reef construction. Coral Reefs 12: 19-30.