IODP

Integrated Ocean Drilling Program

Tahiti Sea Level Expedition

Expedition 310

Environmental Impact Statement

Prepared by the

ECORD Science Operator

in conjunction with Co-chief Scientist G Camoin

September 2005

INTEGRATED OCEAN DRILLING PROGRAM

Health, Safety and Environment Policy

The Integrated Ocean Drilling Program (IODP) is an international research initiative for scientific drilling operations using specifically designed drillships and other platforms. The purpose of IODP is to improve the understanding of the natural process activity on the planet.

IODP is responsible to ensure the health and safety of all personnel in the areas in which it operates and to minimize the impact of its operations on the environment. IODP recognizes the importance of protecting the marine environment, its fauna and flora, and will take the necessary action to minimize potential impacts.

The scientific research program operates around the world and is subject to international and host country Health, Safety and Environment legislation. IODP will ensure that operations meet internationally recognized HSE standards and comply with the requirements of host country legislation, standards, guidelines and codes.

To achieve this, IODP will:

- Provide HSE leadership for operations with evidence of a positive HSE culture and training at all levels.
- Develop HSE specific policies and management practices that comply with international standards.
- Review and track the implementation and performance of the HSE policies. Modify the policies as warranted with changes communicated to all relevant personnel.
- Assure that work performed is conducted according to the agreed upon HSE plan

ECORD SCIENCE OPERATOR

Health, Safety and Environment Policy Statement

The ECORD Science Operator (ESO) is committed to achieving the highest possible levels both of health and safety for personnel and protection of the environment, throughout its MSP operations.

Working within the overall framework of the UK NERC and BGS Health and Safety Policy and Management System, the ESO will aim to comply with and, where practical, exceed the requirements of applicable HSE Legislation, Standards, Guidelines and Codes.

The IODP Environmental Principles will form the baseline for environmental issues.

The ESO will expect all contractors and participating scientists to show equal commitment to these aims.

Within the overall HSE framework the ESO will develop a Mission Specific HSE Plan for each Expedition. This will be achieved by:

- Seeking out, evaluating and implementing the best practice H & S procedures for the particular type of operation. All contractors will be required to comply with this best practice.
- Seeking out, evaluating and implementing the best practice environmental management procedures for the particular environment in which the operations are taking place.
- Conducting detailed risk assessments in advance of any operations.
- Reducing any and all risks identified through appropriate and effective control measures.
- Providing appropriate information, instruction and training.
- Reviewing, auditing and learning from our experience to improve our HSE best practice.

The ESO is fully committed to HSE best practice and in accordance with the IODP HSE Policy.

A C Skinner
ESO Operations Manager   December 2003

1. The Integrated Ocean Drilling Program (IODP)

The Integrated Ocean Drilling Program (IODP) is a multinational program of scientific research in the oceans which uses drilling and logging to undertake research on earth system processes ranging from changes in the earth's climate to the rifting and drifting of continents. The scientific and technical results of the IODP are openly available.

IODP drilling operations focus on a capability provided by three scientific ocean drilling platforms, the *Joides Resolution* provide by the USA, the Japanese drilling vessel *Chikyu,* and mission specific platforms (MSPs) provided by Europe to meet specific objectives of the science plan for shallow water and Arctic drilling that cannot be effectively done through use of the other vessels. The Tahiti Expedition in shallow water is one such MSP operation; as the name implies, MSPs are not a single platform or vessel but will be chosen on a case-by-case basis to best address each scientific problem.

The IODP Tahiti Sea Level Expedition is organised by the ECORD Science Operator (ESO), a consortium of European scientific institutions formed specifically to undertake Mission Specific Platform (MSP) operations for ECORD (European Consortium for Ocean Research Drilling) on behalf of IODP. ESO comprises the University of Bremen, the European Petrophysics Consortium (Universities of Montpellier, Aachen and Amsterdam led by Leicester University), and the British Geological Survey (BGS) who act as the co-ordinator.

ESO undertake MSP science operations on behalf of IODP on the basis of science prioritisation undertaken by the IODP Science Advisory Structure.

2. Background

Living reefs are very sensitive ecosystems. For that reason, any scientific drilling in reef environments must be undertaken with great care in order to exclude or, at least, to minimise the impact of drillings on the reefs (see both IODP and ESO Health, Safety and Environment statements at the front of this document, and also the draft IODP reef drilling guidelines in Appendix I).

Unpublished observations and published monitoring studies concerning oil and scientific drilling in coral reef environments have demonstrated that long-term ecological perturbations can be due to physical destruction of the seabed which provides a substratum for settling organisms. Mechanical effects include crushing of reef substratum by drill rig legs, anchor scars, local smothering of communities by grout or pea gravels and cements bags, and the presence of drilling debris.

One of the main concerns in planning and execution the IODP Tahiti Sea Level Expedition is how the drilling operation itself may impact the local reef environment. In order to determine likely effects both on the seabed and the sub-surface, this study has been carried out into modern reefs in Tahiti and world-wide. Important aspects include the experience of drilling into them, monitoring after drilling, and influences on the water circulation in reef sequences.

ESO have designed the operational aspects of the expedition in such a way as to minimise the impact of the drilling on the environment. The main points relating to these plans are outline at the end of this report.

ESO are grateful to Gilbert Camoin, a co-chief scientist on the expedition, who carried out the background study with the help of other named international scientists

3. Aims of the Tahiti Sea Level Expedition

The history of world-wide sea-level and sea-surface temperature variation associated with the last deglaciation is of prime interest in the context of present-day global warming. Coral reefs are excellent sea-level indicators as their growth keeps pace with sea-level rise. This project seeks to establish the course and effects of the last deglaciation and the associated rise in sea level in a reef setting located far away from glaciated regions through the recovery of the whole post-glacial reef sequence by drilling successive reef terraces seaward of the living barrier reef at three transects around the island.

The study will have three major objectives, full details of which can be found in the Expedition Prospectus (Camoin, Iryu and McInroy, 2005) from which this section is derived.

- To reconstruct the deglaciation curve for the period 20 000 to 10 000 yrs BP in order to establish the minimum sea-level during the Last Glacial Maximum, and to assess the validity, the timing and amplitude of meltwater pulses which are thought to have disturbed the general thermohaline oceanic circulation and, hence, global climate.

- To establish the sea surface temperature variation accompanying the deglaciation and examine the impact of sea-level changes on reef growth.

- To establish patterns of short-term palaeoclimatic changes that are thought to have punctuated the period under investigation and to try to identify specific climatic phenomena such as El Nino-Southern Oscillation (ENSO).

The water depths involved in the drilling range from 40 to 310 m, with two exceptions concerning the drilling of keep-up reefs in the Tiarei and Maraa areas at which water depth are respectively 20 and 30 m. Therefore 16 of the 18 drill sites in the 3 transects are in water deeper than 40 m, which corresponds to the limit where the abundance of the living cover (especially the coral cover) decreases sharply and becomes limited in 40 to 50 m water depth and is almost nil below 50 m.

4. Morphology and physiography of the modern reefs around Tahiti

Knowledge of the morphology and physiography of modern reefs is a prerequisite to assessing the potential impact of drilling operations in reef environments.

The reefs off Tahiti and the neighboring island of Moorea were investigated and monitored for many years by biologists through scuba diving (Bouchon, 1985; Galzin & Pointier, 1985) and submersible dives (Salvat et al., 1985). Morphological studies by echo and seismic profiling, and biological observations, were also carried out aboard the SISMITA in October

2002 (Camoin et al., 2003; Camoin et al., in press). Below is a detailed description of the reef slopes.

4.1. Morphology

Tahiti is surrounded by discontinuous and poorly developed fringing reefs that locally grade into a chain of barrier reefs. These are commonly interrupted or submerged. The barrier reef complex can be subdivided into three zones, from land towards the sea:

(1) The **back-reef zone** corresponds to a 1 km-wide bay, reaching a maximum depth of 20 m. Two large flat-topped patch-reefs, of about 90 000 and 15 000 square metres in areal extent respectively, occur in the central part of the back reef zone. The windward slopes of these are steep with nearly vertical drop-offs along the northern and western margins and relatively gentle leeward slopes on the southern and eastern margins.

(2) The **reef flat zone** is relatively narrow with a maximum width of only 130 m, and consists of three distinct sub zones:

(1) The outermost sub zone (the reef edge).
(2) The intermediate sub zone (patchy reef flat).
(3) The innermost sub zone (rubble reef flat).

The reef flat is connected to the back reef floor through a gently dipping biodetrital talus apron extending over 50 m.

(3) The **outer reef slope** consists of coral-built spurs and grooves, and is characterized by several scarps.

The slope is relatively gentle at an average of 15° average to a water depth of about 15 m, and then steepens to about 20° down to 50 m water depth, including a buttresses and valley zone between 15 and 30 m deep. Between 30 and 50 m depth, the outer slope is characterized by a sediment slope that is slightly inclined to 45 m, and steeper beyond.

Two prominent terraces at 50 m, and 90 to 100 m, were observed during a survey by the submersible *Cyana* (Salvat et al., 1985) and imaged during the SISMITA cruise (Camoin et al. 2003; Camoin et al., in press).

- The extensive terrace recorded at 50–60 m water depth is characterized by the occurrence of build-ups corresponding to relict reefs. The terrace is gently inclined seawards down to 90 m. The reef sequence deposited on top of this terrace forms a sedimentary wedge that pinches out at 90 m depth in the Tiarei area.

- A narrower terrace typically characterizes the depths ranging from 75 to 90–100 m. It displays abundant build-ups that are interpreted as drowned reefs. In the Tiarei area, the height of these build-ups ranges from 30 m (base at 100 m, top at 70 m below sea level), up to 45 m (base at 90 m, top at 45 m below sea level). There is a clear break in slope at 90–100 m where the slope steepens sharply to form a cliff.

The transition zone between 90–100 m and 200–250 m may correspond either to an almost vertical wall or to a steep slope. A significant break in slope has been observed at 120–130 m depth. This zone generally comprises laterally discontinuous ledges and gives the appearance of being highly stratified down to a depth of 200 m. Build-ups up to 45 m high (base at 135 m, top at 90 m below sea level) that occur locally on the slope are interpreted as relict reef ridges.

Below 200 m and down to 500 m depth, the seafloor is characterized by carbonate encrustations that gradually become less abundant down slope where basaltic flows are dissected by detrital talus. Below 500 m, the slope is gentler (10–25 °) with sedimentary deposits (volcanic and coral detritus) and coral debris.

4.2. Biological associations

Specific biological associations as found on the three morphological divisions of the reef at Tahiti:

(1) The **back-reef zone.** The top of the patch-reefs in the back-reef zone corresponds to an exposed reef flat zone dominated by branching corals (*Acropora* gr. *danai/robusta, Pocillopora*), associated with scattered massive *Porites* and faviids. Patchy algal meadows composed of chlorophytes (*Halimeda*) and rhodophytes (*Amphiroa*) are also present.

(2) The **reef flat zone.** The outermost sub zone of the reef flat (the reef edge) exhibits cm-thick crusts of coralline algae (mostly *Hydrolithon*) associated with robust branching acroporids (*Acropora* gr. *danai*/*robusta*). The intermediate sub zone (patchy reef flat) has scattered coral heads including branching (*Acropora* gr. *danai/robusta*, *A. cytherea*, *Pocillopora verrucosa*) and massive (*Porites australiensis, P. lutea*) forms. In the innermost sub zone (rubble reef flat), the floor is chiefly covered by coralgal rubble and living coral colonies are rare (*Acropora*, *Porites*). The reef flat is connected to the back reef floor through a gently dipping biodetrital talus apron, extending over 50 m.

(3)The **outer reef slope.** In the upper part of the spur-and-groove system (from less than 5–6 m to 15 m deep), biological communities are characterized by abundant branching and massive scleractinian corals (*Acropora* of the *robusta/danai* group, *Pocillopora verrucosa, P. eydouxi, P. damicornis, Montipora erythraea, Montastraea curta, Porites lobata*) and hydrocorals (*Millepora platyphylla*) with subordinate domal forms (*Favia, Favites*); secondary framebuilders (i.e. encrusters) are dominated by the coralline alga *Hydrolithon onkodes* associated with *Neogoniolithon, Hydrolithon* sp., *Lithothamnium* and *Lithophyllum*) and vermetid gastropods (*Dendropoma maximus, Serpulorbis annulatus*).

Between 15 and 30 m depth, the biological communities are characterized by a dense coral cover comprised of *Porites* and *Montastrea*. Around 30 m, massive corals (*Porites lutea*) prevail.

Between 30 and 50 m depth, the coral cover decreases sharply on the sediment slope. Below 50 m the living cover is very limited and mostly consists of red algal crusts, scattered laminar coral colonies and small solitary corals.

5. Environmental impact of drilling in coral reef environments

Both oil drilling and scientific drilling have been carried out in coral reef environments worldwide for several decades. These two types of drilling are not necessarily comparable in terms of technical deployments (drilling platforms, drilling depths, drilling techniques), but their combined experience is valuable. Below are summarized unpublished observations and the results of published monitoring studies carried out after both hydrocarbon and scientific drilling.

5.1. Hydrocarbon industry drilling

Drilling operations have been conducted in several areas throughout the World, such as the Gulf of Mexico, western Atlantic, the Caribbean (Trinidad), the Arabian Gulf (off Abu Dhabi), the South China Sea off Sarawak and Palawan (Philippines). The ecological perturbations of such drilling operations may include:

- Physical destruction form the footprints of drilling rigs and anchor scars.
- The deposition of drilling debris, drilling mud and cuttings.

Two areas have been the subject of published post-drilling environmental monitoring studies: the Philippines (Hudson et al., 1982) and Florida (Dustan et al., 1991).

Hudson et al. (1982) examined a drill site in 22 m of water on coral bottom in the Philippines 18 months after drilling and found little mortality directly attributed to drill mud and, to a lesser extent, to cuttings (Hudson et al., 1980). The study developed in Florida is the most comprehensive and concerned seven offshore exploratory wells at water depths varying from 5 to 70 m that were studied between 2 and 29 years after drilling. The objectives of the study was to evaluate the long-lasting environmental impact of drilling on organisms considered important to the coral reef and sea grass ecosystems, particularly reef-building corals, gorgonians, sea grasses, macroalgae and reef fishes. Special emphasis was placed on reef corals. The biological assessment techniques used included chain transects, quadrats, radial transects, probes, submersible observations, sediment sampling and photography and video surveys. The major results of this study are summarized below.

a) Long-term ecological perturbation appeared to be limited to physical destruction and the deposition of drilling debris that provided a substratum for settling organisms. Mechanical effects include crushing of reef substratum by drill-rig legs, anchor scars (approximately 40% of the total damaged area), local smothering of communities by grout or pea gravels and cements bags, and the presence of drilling debris.

b) Significant deposits of drill muds or cuttings were not encountered at any of the sites, regardless of their water depth (5 to 70 m) and there was no evidence of ecological damage from cuttings or drill muds. The lack of drill-cuttings mounds at all sites, despite the several thousand barrels of cuttings that 3000 m wells should produce, was explained by the effects of currents and storms. The authors assumed that cuttings probably had covered portions of the bottom during drilling, but subsequently would have been redistributed into topographic low away from the reef. They cite an unpublished study conducted with remote cameras 24 hours after the rig departed and which also failed to show conclusive evidence of cuttings. None of the sites exhibited evidence of corals, gorgonians, or algae having been killed by drilling fluids or cuttings.

The authors concluded that the communities at all sites examined are similar to those at control areas, with the exception of two sites due to the presence of tons of pea gravel that permanently altered the bottom, and to the drill rig legs and anchors which scarred the reef rock. In some places, the occurrence of drilling debris had positive impact on reef communities as they created artificial reefs encrusted by corals and fleshy algae.

At some sites, the authors were not able to find the drill holes.

The authors concluded that with present technology and stringent dumping regulations, exploratory wells can probably be accomplished without leaving a trace. The results of this study pertained only to exploratory drilling that, unlike production wells that remain in place for tens of years, is a one-time perturbation to the habitat that lasted for a maximum of 1 to 3 months.

5.2. Scientific drilling

Scientific drilling in coral reef environments involve both coral coring and reef drilling. The coring of individual large coral heads has been carried out in many places by a large number of scientists. Although no monitoring data have been published, it has been demonstrated that there was virtually no effect of drilling other than the hole itself, and that plugged core holes. from 2 to 4 inches in diameter are healing. This observation is confirmed by ESO experience of drilling on Ribbon Reef on the Great Barrier Reef where no cuttings were left on the surface which dried out at low tide thus enabling daily observations.

To date, scientific reef drilling campaigns have been carried out in many regions, mostly on modern reef tracts in order to constrain Quaternary sea level changes (see Camoin et al., 2004):

- Great Barrier Reef (Hopley, 1982; Marshall & Davies, 1982; Davies & Hopley, 1983; Hopley et al., 1983; Hopley & Barnes, 1985; Johnson & Risk, 1987; Partain & Hopley, 1989)
- New Caledonia (Coudray, 1976; Cabioch et al., 1995)
- Papua New Guinea (Chappell & Polach, 1991; Edwards et al., 1993)
- French Polynesia (Pirazzoli & Montaggioni, 1988, Bard et al., 1996; Montaggioni et al., 1997; Camoin et al., 1999; Cabioch et al., 1999; Camoin et al., 2001)
- Other Pacific islands (Easton & Olson, 1976; Marshall & Jacobson, 1985; Kan et al., 1995 ; Cabioch et al., 1998)
- Islands in the Indian Ocean (Camoin et al., 1997; Camoin et al., 2004)
- The Caribbean (Adey & Burke, 1976; Macintyre et al., 1981; Lighty et al., 1982; Fairbanks, 1989; Bard et al., 1990a, 1990b; Cortès et al., 1994).

G. Camoin and colleagues have carried out a number of drilling operations in modern reef tracts from various places in the Pacific and Indian oceans (French Polynesia, Great Barrier

Reef, New Caledonia, Western Indian Ocean etc.). They used a variety of drilling systems such as a Sedidrill 500 mounted either on caterpillars on the jetty of the Papeete harbour (Tahiti), a small barge in New Caledonia, and a tractor-mounted rotary drilling rig in the Seychelles.

In most cases, these drilling projects have been carried out on the reef flat zone of living reefs, although spots were selected where coral cover was generally lower. The drilling was in all cases carried out using only seawater as drilling fluid and not introducing any drilling mud. All the reef systems drilled by this team have been subsequently monitored, and it appears that none of the drilling affected the density and the diversity of coral cover. Small amounts of cuttings were produced during the rotation of the bit, but none created piles of cuttings piles. It seems likely that most of the cuttings disappeared in large primary cavities that characterize the reef frameworks. None of the drilling carried out during the last 15 years by the team damaged on living reefs.

Recently, G. Camoin organized a mini-forum on the NOAA Coral List Server (http://coral.aoml.noaa.gov/mailman/confirm/coral-list) to share experiences with others who have carried out scientific drilling in modern reef environments. A summary of the information received from colleagues is presented below:

Dennis Hubbard, Dept. of Geology, Oberlin College

Our drilling system is quite small and is not comparable to larger-scale oil drilling systems. In fact, we have used the system within a US National Park (on a contract from them). We typically hand-set all the anchors on the platform from which we work and place them in a way as to make it impossible for lines to rub against corals, etc. We keep all the power supplies and the rest of the operation on a small barge that is anchored just off the reef. We do most of our drilling underwater, but when we do go up on the reef crest we float the drilling tower (a 3.5 m tripod and guide-way for the drill) onto the reef and assemble it there. Power comes in through hoses that are carefully placed to avoid live corals

The system does produce fine-grained tailings as the bit rotates, but the quantities are small and the duration is short – less than even a storm. Corals have been shown to be very tolerant of even a large dosing of sediment as long as the duration is short. We also try to select spots where coral cover is lower to avoid inadvertent damage due on contact.

There has been follow-up monitoring on Buck Island (we drilled right on the monitoring transects to facilitate comparisons) and the reefs have actually increased their cover since we drilled. However, that is due to the fact that the shallow *Acropora* community had already been devastated by White Band Disease and the remaining reef zones had been severely damaged by Hurricane Hugo. I suppose some clever statistician could use this to prove that drilling is good for coral reefs.

Eugene Shinn, USGS

I can not think of any attempts to monitor effects of coral reef drilling. I have cored many reefs in Florida and was always impressed that no effect could be seen the next day. There seemed to be no reason to monitor. Other than an 8–10 cm diameter hole (which fills in with sand and rubble very quickly) the most visible effect is the clouds of lime mud that comes out of the bore hole while drilling. It sometimes looks like a small snow story around the immediate drill area. If there is any wave action it is gone the next day. We were always to pick a spot where the legs of the tripod would be on sand or bare rock – never on live coral.

Fred Taylor, University of Texas

We had no environmental monitoring. All of the drilling was done on land, although some sites were located just a few meters from the high-tide level. Thus, no valid scientific evidence of the impact, but except for the noise and vibrations, I believe that there was little impact. In all sites (Vanuatu, Papua New Guinea, Solomon's) we used a continuous stream of clean salt water as the drilling fluid and in a couple of instances we used some polymer mud. Of course there was some run off of saltwater and cuttings from the boreholes at the beginning of each hole while we maintained sufficient circulation. However, there was never a very large area of cloudy water from the drilling. The total quantity of material ground up by the drill is not very great and much of it is fairly coarse so that it settles out quickly. In every case, we lost circulation after 10–20 m max., and all of the water we pumped was absorbed by the reef structure. I would guess that nearly all cuttings settled out in reef voids and that water returning to the sea through the reef was relatively clean. I never saw any evidence of cloudiness in the water near shore that would indicate a stream of muddy water entering the sea.

6. Potential impact of drilling on hydrologic conditions

The evaluation of the potential impact of drilling on hydrologic conditions in reef rocks must be based on an accurate reconstruction of fluid circulation in reefs and carbonate islands. Unfortunately, relatively little research has been devoted to the study of internal fluids in atolls (Oberdorfer and Buddemeier, 1986), mainly because of logistical difficulties.

Hydraulic circulations induced by thermal convection in carbonate platforms and atolls are still not well known. Many physico-chemical field data on reef interstitial waters (hydraulic, thermal, geochemical, geological etc.) show a link between the pore water inside the carbonate and the ocean water. For instance, the temperature profiles in the reef and under the lagoon tend to follow the temperature profile of the ocean, for the temperature decreases with depth whereas it usually increases in geological substrates. This suggests that water of oceanic origin circulates within the rock, influencing both its temperature field and its chemical composition.

Previous study of fluid flow in the subsurface of locations in Florida and at Enewetak Atoll have documented the existence of internal geothermal circulation, now often referred to as Kohout circulation (e.g. Saller, 1984).

Samaden et al. (1985) performed the first numerical simulations of the thermo-hydraulic behaviour of an atoll that applies satisfactorily to Enewetak Atoll. Their two dimensional model was based on a simplified geometry of the system and on the average properties of the different formations. The ascent of waters occurs mainly in the peripheral parts, the heated water ultimately diffusing through the floor of the lagoon and, more vigorously, on the outer reef. The calculated vertical upward velocity for mean permeability is 0.4–1.5 cm/day. However, these basic figures obtained from matrix computation could be largely exceeded in view of the relatively open-pore system demonstrated by the petrographic analyzes of the reef cores from Moruroa (Camoin et al., 2001) and Tahiti (Camoin *et al*., 1999; Cabioch et al., 1999).

The geothermal endo-upwelling concept (Rougerie and Wauthy, 1993) links the thermally driven convective circulation of subsurface fluids (i.e. Kohout circulation) with the biological consequences of this physical thermo-convective process on coral reef growth. Drill holes through the barrier reef of Papeete were instrumented with sampling tubes for measurements of physico-chemical parameters in order to test this hypothesis.

A special experimental protocol for the measurement of borehole permeability and extraction of the associated pore waters has been developed for exploratory drill holes (300 m long in average) in Moruroa and Fangataufa atolls (Rougerie and Wauthy, 1993). In the volcanic sequence, the permeability varies from 10^{-16} m^2 to 10^{-13} m^2 with an average of 10^{-14} m^2. Total average permeability for the carbonate sequence is in the order of 10^{-11} m^2 , a medium to high value that strongly contrasts with the low to very low values measured in the volcanic rocks.

Leclerc et al. (1998) modeled the hydraulic circulations using the computer code TRIO/CASTEM developed at the CEA/SEMT, Gif-sur-Yvette (France) and showed that:

- Atolls and carbonate islands are characterized by upward convective circulations. Oceanic water penetrates the atoll of the carbonate body through its flanks. These circulations are mostly due to the temperature gradient in the ocean. The geothermal flux, which intuitively would appear to be the main driving force of the thermo convective circulation is, in fact, of lesser importance.

- The system is highly sensitive to heterogeneities. One of the major heterogeneities influencing the exchange between the interstitial water and the ocean is the occurrence of the transition zone, which is modeled as a highly permeable layer at the top of the volcanic substrate. The high permeability of this zone allows the cold oceanic water to penetrate easily deep into the platform. Buddemeier & Holladay (1977) have already noticed that the occurrence of more-permeable layers influenced the hydrology of Enewetak Atoll. The average Darcy velocity in the transition zone obtained in the present calculations is around 4 cm day^{-1}, whereas its value in the overlying platform is of the order of 0.2 mm day^{-1}.

Although the physico-chemical data in atolls and carbonate islands come from measurements in boreholes, these measurements may not always be representative of the hydraulics of the atoll or the carbonate island as the circuit is modified by the presence of the borehole itself. If the borehole intersects the basal highly permeable zone (at the top of the volcanic substrate), the system becomes an open hydraulic circuit in which the flow is mainly independent of the flow in the carbonate body.

The Reynolds number determines whether a flow is laminar or turbulent. In a pipe, it is expressed as: $Re = UD\rho/\mu,$ where U is the longitudinal velocity, D the diameter, ρ the density of the circulating fluid and μ its viscosity.

The flow is purely laminar if Re is close to 2000 (Roy, 1988) and turbulent when $Re > 6000$. With a borehole diameter of 10 cm, $\rho = 1000$ kg m^{-3} and $\mu = 10^{-3}$ kg m^{-1} s^{-1}, we obtain $Re <$

2000 for velocities < 2×10^{-2} m s^{-1}. This indicates a perfectly laminar state. Thus the flow can be approximated everywhere in the system by Darcy's Law with equivalent permeabilities.

The drilling operations in Tahiti concern reef rocks that lie upon a basaltic bedrock. Both are permeable media but the basalt permeability is between three or four orders of magnitude lower than that of the carbonate (Guille et al., 1993; Samaden et al., 1985). The permeability of limestone and dolomite forming the atolls and the high volcanic islands range from 1mDa to 30 mDa (porosity of about 30%) while the volcanic basement displays permeabilities of less than 1 mDa (Rougerie and Wauthy, 1993).

Reef rocks are highly anisotropic and heterogeneous due to the stratification of the substrates and the occurrence of joints, fractures or karsts. Their porosity, which ranges from mini to megapores, averages 30%, enabling large volumes of interstitial water to saturate the framework. In the boreholes carried out through the modern barrier reef off Papeete, the drilling-rate log demonstrated the occurrence of large megaporosity voids of m^3 to tens of m^3 (Rougerie *et al.*, 1997) which correspond merely to primary cavities. Permeability is variable in the carbonate sequence that ranges from well-cemented limestones to porous chalky carbonates and sands. At the atoll scale, permeability depends greatly on the horizontal (e.g. sedimentary and diagenetic unconformities, karstic horizons) and vertical (e.g. fractures, karstic cavities) structures.

The measurements and experiments in drill holes carried out throughout the Tahiti barrier reef and Moruroa atoll, and the modeling of hydraulic circulations imply that the drilling may influence fluid flows in the reef subsurface, but its impact should be limited compared to the overall circulation in this highly permeable carbonate body that is characterized by the occurrence of large primary cavities.

7. Proposed operational practice

The water depths for the proposed drilling sites in Tahiti range from 35 to 310 m and require the use of a mission specific platform. The DP Hunter, a diving support vessel, has been contracted as the drilling vessel. The drilling contractor is Seacore of Gweek, Cornwall, who will install a drilling derrick on the DP Hunter's aft deck, utilizing a pre-existing moonpool. The DP Hunter is equipped with full dynamic positioning.

All operations carried out off Tahiti will be carried out in such a way as to minimise the impact of the work on the reef environment. Specific aspects include:

- The proposed IODP and ESO statements on the conduct of operations with due regard to the environment shall form the baseline for all area of work. These statements are presented at the front of this document.

- The vessel will operate under the ISM Code, including IMO and SOLAS regulations, and will have its own approved HSE system in operation as required by the ISM Code. Coring, logging and curation operations, although they will have their own specific guidelines, will be interfaced to those of the drilling vessel, as will those of contractors.

- The drilling programme, and the environmental safeguards to be put in place, have been discussed with the appropriate Tahiti Authorities who have issued approval to carry out the drilling in their coastal waters.

- The drilling vessel will hold station using a dynamic positioning system that precludes the use of anchors and decreases the platform footprint to only the drill hole and associated baseplate that lies on the sea bed.

- The baseplate to be employed has a diameter of only 1.5 metres, will have three short legs and a flat base, thus decreasing to an absolute minimum the impact on the sea bed. On location, the drillstring will be positioned by video camera to avoid live corals (see below).

- The dynamic-positioning system is of the most modern type with full backup, thus minimising the likelyhood of the vessel drifting off station and potentially damaging the reef.

- All drilling operations will be completed within a period of less that two months, and it is not anticipated that any one site will be occupied for more than 2–3 days. Any influence on the ecosystem at any one location will therefore be very brief.

- A ‘piggy-back’ mining-type wireline coring system with a conductor to the seabed will create a minimum of cuttings due to the small kerf on the bit, although experience shows that the majority of cuttings are in fact dissipated subsurface while coring This type of equipment has been used extensively in other coral reef situations world-wide and has a good track record.

- The drillstring between the ship and the seabed will be protected by the conductor pipe. This provides a conduit to the vessel for any cuttings that do come to surface. Even so, no significant deposits of cuttings were encountered at any of the sites drilled for either oil exploration or scientific studies, regardless of their water depth or the topography of the sea-floor, even for 3000 m-deep wells.

- Seawater will be used as the drilling lubricant in place of mud, thus eliminating the possibility of the accumulation of drilling-mud deposits.

- At all sites, a high-resolution colour video camera, with recording facility, will be deployed through the drillstring in order to:

  (1) Establish that the precise location of the drill sites are on sand or bare rocks, thus avoiding living coral heads.
  (2) Carry out post-drilling examination of the site.
  (3) Provide a record of environmental impact at the site.

From the above data and experience acquired during many years of scientific drilling in the Pacific and Indian oceans, and the implementation of the drilling strategies defined above, it is anticipated that the offshore drilling in Tahiti will not have any significant impact on living reefs.

8. References

Adey, W.H. & Burke, R., 1976. Holocene bioherms (algal ridges and bank barrier reefs) of eastern Caribbean. Geological Society of America Bulletin, 87 (1), 95-109.

Bouchon, C. 1985. Quantitative study of scleractinian coral communities of Tiahura reef (Moorea Island, French Polynesia). Proc 5th Int Coral Reef Cong, 6, 279-284.

Bard, E,, Hamelin, B., Arnold, M., Montaggioni, L., Cabioch, G., Faure, G., & Rougerie, F., 1996. Sea level record from Tahiti corals and the timing of deglacial meltwater discharge. Nature, 382, 241.

Bard, E., Hamelin, B., & Fairbanks, R.G., 1990a. U-Th ages obtained by mass spectrometry in corals from Barbados: sea level during the past 130,00 years' . Nature, 346, 456.

Bard, E., Hamelin, B., Fairbanks, R.G., & Zindler, A., 1990b. Calibration of the ^{14}C timescale over the past 30,000 years using mass spectrometric U-Th ages from Barbados corals. Nature, 345, 405.

Buddemeier, R.W., & Holladay, G.L. 1977. Atoll hydrology, island ground-water characteristics and their relationship to diagenesis. In: Proceedings of the 3rd International Coral Reef Symposium, 2, 167-174.

Cabioch, G., Montaggioni, L.F. & Faure, G., 1995. Holocene initiation and development of New-Caledonian fringing reefs, SW Pacific. Coral Reefs, 14 (3), 131-140.

Cabioch, G., Taylor, F.W., Recy, J., Lawrence Edwards, R., Gray, S.C., Faure, G., Burr, G.S. & Correge, T. 1998. Environmental and tectonic influence on growth and internal structure of a fringing reef at Tasmaloum (SW Espiritu Santo, New Hebrides island arc, SW Pacific). Int Assoc Sediment Spec Publ, 25, 261–277.

Cabioch, G., Camoin, G.F. & Montaggioni, L.F. 1999. Postglacial growth history of a French Polynesian barrier reef tract, Tahiti, central Pacific. Sedimentology, 46, 985.

Camoin, G., Cabioch, G., Gautret, P., & Montaggioni, L.F., 1999. Nature and environmental significance of microbialites in Quaternary reefs: the Tahiti paradox. Sedimentary Geology, 126, 271.

Camoin, G., Colonna, M., Montaggioni, L.F., Casanova, J., Faure, G., & Thomassin, B.A., 1997. Holocene sea level changes and reef development in southwestern Indian ocean. Coral Reefs, 16, 247.

Camoin, G., Cabioch, G., Hamelin, B. & Lericolais, G., 2003. Rapport de mission SISMITA. 20 p. + figures et tableaux.

Camoin, G., Cabioch, G., Eisenhauer, A. & Braga, J.-C., in press. Environmental significance of microbialites in reef environments during the Last Deglaciation. Sedimentary Geology.

Camoin, G.F., Montaggioni L.F. & Braithwaite, C.J.R., 2004. Late glacial to post glacial sea levels in the western Indian ocean. Marine Geology, 206 (1-4), 119-146.

Camoin, G., Ebren, Ph., Eisenhauer, A., Bard, E. & Faure, G., 2001. A 300,000 years record of sea level changes, Mururoa atoll (French Polynesia). Palaeogeography, Palaeoclimatology, Palaeoecology, 175, 325.

Camoin, G., Cabioch, G., Gautret, P., & Montaggioni, L.F., 1999. Nature and environmental significance of microbialites in Quaternary reefs: the Tahiti paradox. Sedimentary Geology, 126, 271.

Cortès, J., Macintyre, I.G. & Glynn, P.W. 1994. Holocene growth history of an eastern Pacific fringing reef, Punta Islotes, Costa Rica. Coral Reefs, 13, 65-73.

Coudray, J. 1976. Recherches sur le Néogène et le Quaternaire marins de la Nouvelle-Calédonie. Contribution de l'Etude Sédimentologique à la Connaissance de l'Histoire Géologique Post-Eocène de la Nouvelle-Calédonie. Expédition Française sur les Récifs Coralliens de la Nouvelle-Calédonie. Fond. Singer -Polignac, Paris, 8, 1-276.

Davies, PJ & Hopley, D. 1983. Growth fabrics and growth-rates of Holocene reefs in the Great Barrier-Reef. BMR Journal Of Australian Geology & Geophysics, 8 (3), 237-251.

Dustan, P., Lidz, B.H. & Shinn E.A. 1991. Impact of exploratory wells, offshore Florida - a biological assessment. Bulletin of Marine Science, 48 (1), 94-124.

Easton, W.H. & Olson, E.A. 1976. Radiocarbon profile of Hanauma-reef, Oahu, Hawaii. Geological Society of America Bulletin, 87 (5), 711-719.

Edwards, R.L., Beck, W.J., Burr, G.S., Donahue, D.J., Chappell, J.M.A., Bloom, A.L., Druffel, E.R.M. & Taylor, F.W., 1993. A large drop in atmospheric $^{14}C/^{12}C$ and reduced melting in the Younger Dryas, documented with ^{230}Th ages of corals. Science 260, 962..

Fairbanks, R.G., 1989. A 17,000 year glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation. Nature 342, 637.

Galzin, R. & Pointier, J.P. 1985. Moorea Island, Society archipelago. In: Delesalle, B., GaIzin, R. & Salvat, B. (Eds.). 5th International Coral Reef Congress, Tahiti. Coral Reef Congress, Tahiti, French Polynesia, 75-101.

Guille. G., Goutière, G., Sornein, J.F. 1993. Les atolls de Mururoa et de Fangataufa (Polynésie française) : géologie, pétrologie, hydrogeology, pp 168 + illustrations.

Hudson, J.H, Shinn E.A. & Robbin, D.M. 1982. Effects of offshore oil drilling on Philippine reef corals. Bulletin of Marine Science, 32 (4), 890-908.

Hudson, J.H. & Robbin, D.M. 1980. Effects of drilling mud on the growth rate of the reef-building coral, *Montastraea annularis*. Drilling Fluid Symposium. API Publ. No. 4284. pp. 1101-1122.

Hopley, D. 1982. The geomorphology of the Great Barrier Reef: Quaternary development of coral reefs. John Wiley-Interscience, New York, pp 453.

Hopley, D., Slocombe, A.M., Muir, F. & Grant, C. 1983. Nearshore fringing reefs in North Queensland. Coral Reefs, 1, 151-160.

Hopley, D. & Barnes, R.D. 1985. Structure and development of a windward fringing reef, Orpheus Island, Palm Group, Great Barrier Reef. Proceedings of the Fifth International Coral Reef Symposium, Tahiti, 1985, 3, 141-146.

Johnson, D.P. & Risk M.J. 1987. Fringing-reef growth on a terrigenous mud foundation, Fantome Island, central Great-Barrier-Reef, Australia. Sedimentology, 34 (2), 275-287.

Kan, H., Hori, N,, Nakashima, Y. & Ichikawa, K. 1995. The evolution of narrow reef flats at high-latitude in the Ryukyu islands. Coral Reefs, 14 (3), 123-130.

Leclerc, A.-M., Broc D. & Jean-Baptiste, Ph. 1998. Steady-state interstitial circulations in an idealized atoll reef and tidal transients in a deep borehole by computer simulation. In : Camoin, G.F. & Davies, P.J. (Eds.), Reefs and Carbonate Platforms in the Pacific and Indian Oceans. I.A.S. Special Publication, 25, 249-258, Blackwell.

Lighty, R.G., Matintyre, I.G., Stuckenrath, R. 1982. Aeropore palmara reef framework: a reliable indicator of sea level in the western Atlantic for the past 10,000 years. Coral Reefs. 1. 125-130.

Macintyre, I.G, Burke, R.B. & Stuckenrath, R. 1981. Core holes in the outer fore reef off Carrie Bow Cay, Belize: A key to the Holocene history of the Belizean Barrier Reef complex. Proceedings, Fourth International Coral Reef Symposium. University of the Philippines, Quezon City, Philippines, 1, 567-574.

Marshall, J.F. & Davies, P.J. 1982, Internal structure and Holocene evolution of One Tree Reef, southern Great Barrier Reef. Coral Reefs, 1, 21–28.

Marshall, J.F. & Jacobson, G. 1985. Holocene growth of a mid-pacific atoll - Tarawa, Kiribati. Coral Reefs, 4 (1), 11-17.

Montaggioni, L.F., Cabioch, G., Camoin, G.F., Bard, E., Ribaud-Laurenti, A., Faure, G., Déjardin, P. & Récy, J. 1997. Continuous record of reef growth over the past 14 k.y. on the mid-Pacific island of Tahiti. Geology, 25, 555.

Oberdorfer, J.A. & Buddemeier, R.W. 1986. Coral-reef hydrology - field studies of water-movement within a barrier-reef. Coral Reefs, 5 (1), 7-12.

Partain, B.R. & Hopley, D. 1989. Morphology and development of the Cape Tribulation Fringing Reefs, Great Barrier Reef. Australia Great Barrier Reef Marine Park Authority, Technical Memorandum, 21.

Pirazzoli, P., Montaggioni, L. 1988. Holocene sea level changes in French Polynesia. Palaeogeography, Palaeoclimatology, Palaeoecology, 68, 153-175.

Rougerie, F., Fichez, R. & Déjardin P. 1997. Geomorphology and hydrogeology of selected islands of French Polynesia: Tikehau (Atoll) and Tahiti (Barrier Reef). In : Vacher, H.L. & Quinn, T.M. (Eds.). Geology and Hydrogeology of Carbonate Islands, Dev. in Sedimentology, 54, 475-502, Elsevier.

Rougerie, F. & Wauthy, B. 1993. The endo-upwelling concept - from geothermal convection to reef construction. Coral Reefs, 12 (1), 19-30.

Roy, D.N. 1988. Applied fluid mechanics. New York: Halsted Press.

Saller, A.H, 1984. Petrologic and geochemical constraints on the origin of subsurface dolomite, Enewetak Atoll - an example of dolomitization by normal seawater. Geology, 12 (4), 217-220.

Samaden, G., Dallot, P. & Roche R. 1985. Atoll d'Eniwetok. Système géothermique insulaire à l'état naturel. La Houille Blanche, 2, 143-151.

Salvat, B., Sibuet, M., & Laubier, L., 1985. Benthic megafauna observed from the submersible << Cyana >> on the fore-reef slope of Tahiti (French Polynesia) between 70 and 100 m. Proceedings of the 5th International Coral Reef Congress, 2, 338.

Appendix I

IODP Reef Drilling Guidelines

DRAFT

This document has not yet been approved by the IODP Environmental Protection and Safety Panel

IODP has adopted a series of three basic principles.

1. Ecological perturbations to the reef ecosystem should be minimized by adopting drilling practices that limit physical destruction of both live and dead reefs, wherever and whenever possible.

2. The accumulation of drilling-related detritus on the seafloor should be minimized.

3. Pre- and post-drilling environmental assessment of the reef drill sites should be made. The results of these assessments should be carefully reviewed from an ecological impact perspective.

A series of general guidelines have been developed to aid in the implementation of these principles. EPSP while reviewing each drill site will consider operational plans to insure that the program's basic principles are not violated and that the environmental impact is minimized.

MECHANICAL DAMAGE

Mechanical damage includes the hole itself (including the impact of the drilling tools and the casing or liner that may be left behind) and that caused by the anchoring of the drilling platform. Damage can be minimized through the selection of spud-in locations outside the "nest" of corals. This will require a visual inspection of the proposed spud-in site using either divers in shallow water or ROV's. EPSP will provide approval within a defined circle centered on the specified drilling site in order to permit the locating of the drill hole outside of the coral "nest". It is recommended that the drilling platform not require anchoring, i.e., a dynamically positioned drilling platform is preferred. However, if a dynamically positioned platform is not selected a floating platform using cemented anchor bolts should be considered. The US Navy has developed such an anchoring system. A post-drilling visual survey also needs to be performed in order to document what, if any, physical disturbance has occurred. It is also recommended that if liners or casing are used that they should remain in-place. Removal of the liners could cause more damage than if they are left in-place.

CUTTINGS AND MUD

The introduction of cuttings and drilling mud may inhibit photosynthesis of symbiotic algae and directly stress the reef. Laboratory and field studies indicate that corals can tolerate some drilling mud and natural sediment. Most cuttings and mud disappear into reef porosity. This loss largely occurs as a result lost circulation within the reef. At some critical threshold if the returns go to the seafloor turbidity and sediment build-up may inhibit the reef's ability to feed and photosynthesize. The hole diameter currently employed by the program would produce only minimal amounts of cuttings. The volume of which should not impact the reef. Furthermore these drill cuttings would be composed of $CaCO_3$ which should not be toxic to the reef. Chronic exposure to sediment or drilling mud is considered much more of a problem than the short-lived drilling associated with IODP activities. Cuttings and mud that are not lost within the reef and are returned to the seafloor are normally dispersed by currents and wave actions. It is, therefore, recommended that as part of the site safety package information on currents and waves be provided to EPSP.

To minimize the effects of drilling fluids it is recommended that seawater be the primary drilling fluid. If some other drilling fluid is to be used the operators may wish to consider the use of biodegradable vegetable-based fluids (e.g., a guar gum drilling fluid) and should also consider using a circulating system to capture the drilling fluid. The safety package should include a detailed summary of the operational plans.

LEAKS OF HYDRAULIC FLUIDS

Leaks or spills of hydraulic fluids and other petroleum products may occur during routine operations. Under normal circumstances any such spills or leaks would be limited in scope (on the order of liters) but could have a negative impact on the ecosystem. The program might consider using a freshwater or seawater hydraulic fluid system or a biodegradable hydraulic fluid to further minimize the risks. It is also suggested that the operator maintain an absorbent which can be employed if a spill occurs.

CHANGES TO REEF CIRCULATION

Changes in how fluids circulate over and through a reef might be deleterious to reef organisms or the physical integrity of the reef. The borehole may negatively impact reef organisms or undermine reef integrity through the introduction of borers (fungi, sponges, and bacteria?). It is unclear what the borehole might do to the internal circulation of the reef itself because of the presence of voids and its high permeability. The internal circulation of reefs is poorly understood, complex, and may include endo-upwelling. Barriers to flow may develop when and where the reef was subjected to subaerial exposure. In order to minimize hydrologic effects it is suggested that the upper few meters of the borehole be plugged and cemented. This would prevent the borehole from potentially becoming a submarine spring, which could impact surface organisms.

NOISE AND VIBRATIONS

Vibrations and noise from drilling and support vessels will be continuous during drilling operations. Noise and vibrations may impact life associated with the reef. It is anticipated that life on some area of reef will be severely disrupted and many mobile species will leave. The time at one site should, therefore, be minimized and there should be separation between sites. Part of the safety package for reef drilling should include an operational summary including anticipated time on location and the proposed drilling order.