# ISLANDS AND BASINS: CORRELATION AND COMPARISON OF ONSHORE AND OFFSHORE GEOLOGY[1]

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## FOREWORD

STAR was founded in 1985 as a vehicle to assist the international geoscience community to provide advice to SOPAC on Science, Tectonics and Resources in the SOPAC region particularly during the intervals between SOPAC International Workshops, the fourth of which was held in Canberra in 1989. The first Chairman of STAR, Dr Charles Helsley, Director of the Hawaii Institute of Geophysics, guided STAR until 1992 when I took over the helm.

Until this year STAR Meetings have been held prior to the Annual Sessions of SOPAC. They have lasted several days and have provided ample time for technical presentations and discussion of issues in both Working Groups and Plenary Sessions, followed by the preparation of a report with recommendations to SOPAC that has been presented at the Annual Session. This year STAR has been merged into the SOPAC Annual Session and I believe this pattern will continue in future years. This is a much tighter schedule than hitherto, and participants will have to be inventive (and forebearing) if we are to properly fulfill our obligations to SOPAC.

STAR is not merely a technical meeting at which scientific papers are presented and results and implications are discussed. It has the additional responsibility to formulate advice to SOPAC concerning its work program and to highlight technical and scientific issues of particular importance or urgency. This year, and in future, we will have less time to formulate (and write!) advice. I will therefore be expecting all participants to assist in finding new ways for STAR to fulfill its advisory role in a timely manner.

One of the great strengths of SOPAC is its ability to mobilise excellent science and bring it to bear so as to address the national needs of SOPAC's island member countries. The long-established working relationship between SOPAC and the international research community is a vital element in this endeavour, which STAR is charged to nurture. This relationship stimulated an order-of-magnitude change in the geoscience database in the SOPAC region during the 1980's (Crook et al., 1991).

Traditionally STAR has been primarily concerned with "blue-water" marine geoscience, tectonics and resources, as its full name implies. However, STAR participants must be sensitive to changing national needs and priorities, so as to ensure that the relationship between SOPAC and the scientific community remains a relevant and working one. SOPAC's 1994 Work Program and its draft Medium-Term Plan, which all participants should examine, contain a great deal of work in fields that are not "blue-water" geoscience. The challenge here is to broaden the spectrum of participation in STAR so that the SOPAC Work Program and its forward planning are influenced by international science that is both excellent and relevant. SOPAC's track record demonstrates that this approach is synergetic, forwarding both national needs and fundamental research. I commend it to you.

Keith A W Crook
Chairman, STAR
16 September 1993

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Reference

Crook, K.A.W., Exon, N.F. and Coleman, P.J., 1991: A decade of growth in the South Pacific marine geoscience database. *Marine Geology*, 98: 155-165.

## EARLY TERTIARY ROCKS IN FIJI

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The oldest rocks in Fiji belong to the Yavuna Group of southwest Viti Levu. These represent part of an Upper Eocene to Lower Oligocene volcanic arc (Yavuna Arc) and were probably rifted to their present position during the formation of the South Fiji Basin in the mid-Oligocene. They are unconformably overlain by the Upper Oligocene to Middle Miocene Wainimala Group which includes volcaniclastic turbidites, hemipelagic carbonates and tuffs deposited in the Sigatoka sedimentary basin, and further south volcaniclastic rudites, dacite and andesite lavas, and minor reef/platform limestones representing the Wainimala arc terrane. The Sigatoka Basin is floored by Wainimala pillow basalts and Yavuna Group rocks and is interpreted as an intra or forearc half-graben that may have originated during mid-Oligocene arc rifting. During the Late Oligocene to MIddle Mioene Fiji was on line with similar arc-forearc systems in Lau-Tonga and Vanuatu as part of a continuous Melanesian Arc.

Increased epiclastic input to the Sigatoka Basin and the deposition of reef/platform limestones, including a major redeposited carbonate horizon, along the southern basin margin, suggest increased emergence of the Wainimala arc during the later Early and early Middle Miocene. This trend culminates in a mid-Miocene sedimentary hiatus during which tonalite/gabbro stocks of the Colo Plutonic Suite were emplaced along the Wainimala arc axis. The sedimentary record in the Sigatoka Basin recommences in the Late Miocene with the development of a sand-rich turbidite system (Tuva Group) fed from the uplifted post-Colo arc masif. These rocks rest on the Wainimala Group without angular unconformity.

An intra-CN9 nannozone angular unconformity separating the Tuva Group from the overlying Navosa Group is interpreted as marking the onset of strike slip tectonism as the Melanesian Arc began to break up with the opening of the North Fiji Basin in the Late Miocene.

## PRELIMINARY ESTIMATES OF SEDIMENTATION RATES IN MODERN CONVERGENT MARGIN-RELATED BASINS IN PAPUA NEW GUINEA

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Various on-land Cenozoic sedimentary sequences in the SOPAC region have been interpreted as convergent margin-related. Criteria from the sequences themselves can be used to substantiate such interpretations. However, one such criterion - measured sedimentation rates - is of little use because of the paucity of comparative data from modern W and SW Pacific convergent margin-related basins.

This paper is a preliminary step towards filling this gap in our knowledge. It is preliminary because isotopic dates have yet to be obtained from the sediment cores under discussion. Nevertheless, the stratigraphy of the cores enables estimates of sedimentation rates to be made, using some reasonable assumptions and comparison with data from Russian work in the region. Barash and Kuptsov (in press) report a sedimentation rate of 15.5 cm/ka during the past 11,500 years, based on five $^{14}C$ dates from the top 1.75 m of a core collected near the Manus Spreading Center (Manus backarc basin) during the 21st cruise of R/V "Akademik Mstislav Keldysh" in 1990.

During the PacManus II cruise of R/V "Franklin" in June 1993, cores were collected in the eastern Manus Basin, PNG (Binns et al. 1993). Several contain thin pale felsic ash layers (Table 1A). These, and the absence of the felsic ash layers at comparable depths in other cores (Table 1B), imply sedimentation rates up to 41.7 cm/ka in the eastern Manus Basin, taking the rate of 15.5 cm/ka from the Manus Spreading Center as a minimum value for purposes of calculation. These rates appear reasonable, considering that the eastern Manus Basin is an enclosed region, close to land.

In front of the South Bismarck volcanic arc, the principal marine depocenters are the western New Britain Trench and the 149° Embayment in the western Solomon Sea. Sediment cores were collected from this area by the R/V "Mahi" in 1970 and the R/V "Moana Wave" in 1992. The "Mahi" cores (M70, Table 1C) consist of approximately 3 m of hemipelagite muds and thin f-vf sand turbidites with rare ash layers that, in M70 PC52, overlie an older sandy turbidite sequence. The abrupt termination of this older thick turbidite sequence is attributed to the drowning of the adjacent Trobriand Platform source area which, for the purposes of this analysis, is assumed to have occurred at 9 ka (msl: -35 m, Chappell and Polach, 1991). The implied sedimentation rate for the overlying hemipelagic sequence is 33 cm/ka. Although these cores are further from land than those in the eastern Manus Basin, the sedimentation rates implied are comparable. This seems reasonable given the large sediment load supplied by numerous rivers, including the Markham River, that debouch into the western Solomon Sea.

Using the estimated sedimentation rate of 33 cm/ka, the youngest ash layer in core PC53 has an age of 0.515 ka. None of the cores taken from the western New Britain Trench depocenter contain this ash layer. Assuming that none of these cores penetrated deeply enough to sample the youngest ash layer, a minimum sedimentation rate can be estimated at 318 cm/ka or 3.18 km/Ma. This accords with known turbidite sedimentation processes in the western New Britain Trench (Krause et al, 1970).

The island of New Guinea is in part continental and to that extent is atypical of much of the SOPAC region. Certainly sedimentation rates in the western Solomon Sea are strongly influenced by the arc-continent collision presently occurring along the Ramu-Markham Suture Zone in NE PNG. The backarc sedimentation rates in the Manus Basin may not be similarly influenced because the principal rivers draining the collision zone, the Ramu and Sepik, debouch into the Bismarck Sea far to the west of the sampling sites. However, little is known about the dispersal pattern of the suspended sediment plumes from these rivers. Given the very high near-surface current velocities recorded in both the St Georges Channel between New Britain and New Ireland and the Vitiaz Strait between New Britain and New Guinea, the suspended sediment from these rivers may be widely distributed throughout the surface waters of the Bismarck Sea. Thus, these estimated sedimentation rates are best treated as representing the more continental-influenced end of a spectrum of values applicable to the SOPAC region.

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Table 1: Data on cores from PNG convergent margin-related basins.

| Core | Depth (thickness) of ash layers (cm) | | Length of core (cm) | sedimentation rate (est. cm/ka) |
|---|---|---|---|---|
| | Layer I | Layer II | | |
| **A: Eastern Manus Basin, cores with ash layers** | | | | |
| MS-15 | 30.5-34.5 (4.0) | 37.5-39.5 (2.0) | | 15.5 |
| MS-17 | 64.0-66.5 (2.5) | | | 32.5 |
| MS-18 | 39.5-40.5 (1.0) | 55.5-57.0 (1.5) | | 20 |
| MS-19 | 38.0-41.0 (3.0) | 56.0-59.5 (3.5) | | 19.3 |
| **B: Eastern Manus Basin, longer cores without ash layers** | | | | |
| MS-9 | - | - | 55.0 | >28 |
| MS-16 | - | 123.0 | | ≥41.7* |
| **C: western Solomon Sea cores** | | | | |
| | Layer A | Layer B | top of thick turbidites | |
| M70 - PC52 | section lost | 278-280 (2.0) | 298 | 33 |
| M70-PC53 | 17.0-19.0 (2.0) | 289-296 (7.0) | absent length of core | |
| MW9204 PC03 | - | - | 142 | ≥276 |
| MW9204-PC06 | - | - | 164 | ≥318 |

*corrected for presence of 41 cm dacitic ash bed

## EVOLUTION OF THE LAU BASIN: IMPLICATIONS FOR THE GEOLOGY OF ARC-BACKARC SYSTEMS OF THE SOPAC REGION

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The southwestern Pacific Ocean basin has an array of (formerly) extensional basins, separated by remnant volcanic arcs, that span more than 350° of longitude. They range in age from the Late Cretaceous Tasman Sea to the Oligocene-Early Miocene (?) South Fiji Basin. The North Fiji Basin, Havre Trough, and Lau Basin represent the most recent sites of crustal extension and magmatism that has formed new seafloor. Like the West Philippine Sea Mariana, Izu, Bonin systems, the region is important for understanding the earliest stages in the sequence of events that culminates in the amalgamation of fragments of arcs and seafloor crust to continental platforms. In the SOPAC region we see the same types of crustal material now represented by "exotic terranes" of both eastern and western North America.

In the SOPAC region, as well as at other intra-oceanic convergent plate margins, subduction-related arc volcanism has formed new crust that ranges in composition from oceanic (basalt/gabbro) to "continental" (low-K rhyolite/ granodiorite). The extensional basins are floored by oceanic crust having MORB-like to arc-tholeiitic chemistry. Subduction has played a major role in the generation of the arc magmas, but the petrogenetic processes are complex. Decompression melting of mantle diapirs, reaction between melt and conduits, assimilation, and fractionation all are involved. The consensus is that depleted supra-subduction zone (SSZ) mantle is the major source. Variable contributions are derived from subduction-derived fluids, including partial melts, and from mantle counterflow above the subduction zone. Similar sources and melting processes control backarc magmatism, but subduction-derived fluids are much less important.

Results of recent ODP drilling in western Pacific arc-backarc systems, together with data from many years of marine surveys, have given new insight to the tectonic and magmatic processes operative in these tectonic systems. These data allow us to propose a revised model for modern arc-backarc systems that may be applicable to "fossil" systems and serve as a guide for their further study. The tectonic processes that have operated at these intra-oceanic convergent margin systems have been dominated by crustal extension. In the Lau Basin, we recognize two major tectonic styles/events. Initially crustal extension and rifting, beginning at about 6 Ma, formed a series of north-trending grabens and horsts (like Basin-Range structures of western USA). These basins formed at the eastern side of the Lau Ridge rather than along the active volcanic chain. Evidence of rifting from about 4.5-2 Ma is found on the Lau Ridge. Lau Ridge volcanism continued while the Lau Basin opened; there is no evidence that active Lau Ridge volcanoes were split away and rifted eastward.

Subsequent to the beginning of basin extension (about 5.5-4 Ma), a rift propagated south from the Peggy Ridge and formed new crust by seafloor spreading on the Eastern Lau Spreading Center (ELSC). Presently the apex of the ELSC is at Valu Fa Ridge. A second propagator was initiated at about 1.5-1.2 Ma and formed the Central Lau Spreading Center (CLSC). Yet another neovolcanic zone, representing crustal extension where the Tonga Trench bends sharply to the west, is in the northeastern Lau Basin. Here three spreading ridges form the Mangatolu (or King's) Triple Junction. Mantle-derived magma leakage has accompanied all of the backarc tectonism.

The extensional basins are ponds of basaltic lava emplaced over time spans of 1.7 my or more. Their magnetic anomaly patterns cannot be matched to symmetric counterparts. ODP Leg 135 drill cores show these ponds to have MORB-like crust. Seafloor spreading on the ELSC and CLSC laid down symmetric magnetic stripes and formed welts of new MORB-like crust on the CLSC and both MORB-like crust, and crust transitional to arc composition, on the ELSC. In addition to the MORB-like fill of the extensional basins, numerous small, ephemeral, arc-composition edifices formed within the Lau Basin as it was rifted. Their presence is indicated by volcaniclastic debris and small flows.

A wave of arc-composition volcanism may have migrated across the basin, tracking the "roll-back" of the Tonga Trench. These intrabasin arc volcanoes probably are not unique to the Lau Basin and their analogues should appear in ophiolites (plagiogranite?). The Tofua Arc is not genetically related to the Lau Ridge and must be a new feature superposed on the rifted forearc of the Lau Ridge. Its age of inception may vary along strike from about 3 Ma at Tafahi to less than 1 Ma near Ata. Volcanism on the Tofua Arc may have migrated southward in consort with the propagating backarc spreading centers.

Much remains to be done in understanding the timing of magmatic/tectonic events in the SOPAC region. Continued detailed studies of rock ages, magma chemistry and tephra-chronology on islands in the region will be important in this venture.

## PACIFIC PLATE MOTIONS, 0-150 MA, IN THE HOTSPOT FRAME OF REFERENCE

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Pacific plate motions based on the hotspot frame of reference have been identified back to 150 Ma. At least four major changes in Pacific plate motion paper to have occured in the late-Jurassic - Early Cretaceous. These changes occurred at approximately 145, 125, 110, and 100 Ma. Hotspot traces defined by rotation poles for the intervening timespans correlate with most Western and Central seamount chains. The most pronounced change in motion at 125 Ma, probably concomitant with the end of southwestward subduction beneath northeastern Gondwana and the beginning of northwestward subduction beneath eastern Eurasia, was also followed by formation of the world's largest oceanic flood basalt plateau, the Ontong-Java Plateau, at 123 Ma.

Southwest Pacific paleogeography has also been reconstructed and animated back to 100 Ma. Plate circuits for all key tectonic elements have been determined with respect to the Indo-Australia (I-A), Antarctica, and Pacific plates, using hotspot trails on the India, Australia, and Pacific plates to constrain the motions of all the plates. Paleo-locations of rifted continential margins, oceanic plateaus, subduction zones, and marginal basins are displayed in 0.5 m.y. steps that provide a simple graphic portrayal of the complex plate motions that have occurred in the Southwest Pacific during the last 100 m.y.

Successive periods of convergence are shown occurring along five different paleo-subduction zones that formed concomitantly with changes in I-A and Pacific plate motions from the Eocene to the late Miocene along the Papuan-Rennell-New Caledonia-Norfolk (55-40 Ma), Manus-North Solomon-Vitiaz (43-25 Ma), New Guinea-proto-Tonga-Kermadec (27-10 Ma), New Britain-San Cristobal-New Hebrides (12-0 Ma), and Tonga-Kermadec (10-0 Ma) trenches.

Episodes of basin information are shown occurring along the western and southwestern margins of the Pacific Plate and along the eastern and northeastern margins of the I–A Plate from the Late Cretaceous to the present, including the Tasman (85-55 Ma), New Caledonia (74-65 Ma), Coral Sea (65-53 Ma), Loyalty (52-40 Ma), D'Entrecasteaux (34-28 Ma), Caroline (34-27 Ma), Solomon Sea (34-28 Ma), South Fiji (34-27 Ma), Caroline (34-27 Ma), Solomon Sea (34-28 Ma), South Fiji (34-27 Ma), North Fiji (10-0 Ma), and Lau, Woodlark, and Manus (5.5-0 Ma) basins. Seamount chains are also shown developing over the Tasmantid, Lord Howe, Louisville, and Samoa hotspots.

## CENOZOIC COMPRESSIONAL TECTONICS ON THE FAIRWAY RIDGE AND THE LORD HOWE RISE BETWEEN NEW CALEDONIA AND AUSTRALIA

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*The data acquired across the 23°S Transition Zone, south of the Fairway Ridge, during the Zoesis cruise, reveal the occurrence of overthrusts which affect the "Fairway Ridge -*

*Lord Howe Rise" area west of New Caledonia. They are synchronous with the late Eocene thrusting of the ophiolitic belt over New Caledonia basement. The late Eocene regional unconformity is interpreted to be result of tectonism. A new bathymetric map is presented and the tectonic history of the Fairway Ridge-Lord Howe Rise complex is proposed. The Lord Howe Rise does not have a "simple continental crustal structure" and could be, like the Fairway Ridge, of oceanic nature.*

New Caledonia belongs to the Internal Melanesian Zone which is characterised by a succession of aseismic ridges and basins created since the Paleocene by stretching of the eastern margin of Gondwana (Aubouin, 1982; Kroenke, 1984). These aseismic features strike along two main trends, NW-SE and N-S. The NW-SE to N-S change of structural direction occurs at the 23°S Transition Zone.

The interpretation of the Single Channel Seismic profiles obtained from the Zoesis cruise (onboard the ORSTOM R/V "L'Alis") allows us to define the structure of the 23°S Transition Zone. From a stratigraphic viewpoint, data from Leg 21 DSDP Boreholes 206 and 208 (Burns, Andrews et al., 1973), Leg 90 DSDP Borehole 587 (Kennett and von der Borch, 1985) and the geological history of New Caledonia (Lillie and Brothers, 1970) enable us to date, within the Fairway and the New Caledonia Basins, three main seismic units (III,II and I).

The seismic-reflection profiles also reveal the existence of overthrusts both on the Lord Howe Rise and its eastern flank and on the southern part of the Fairway Ridge. We consider these overthrusts to result from the thrusting of the ophiolitic belt over the New Caledonia basement at the end of the Eocene (Paris, 1981), creating compressive constraints west of New Caledonia. The strong positive magnetic character of the Fairway and Norfolk Ridges (Eade, 1988) and marine magnetic anomalies identified over the Lord Howe Rise (Schreckenberger et al., 1992), suggest that the crust between the Lord Howe Rise and the Norfolk Ridge is oceanic including that beneath the Fairway Ridge, and the submerged Lord Howe rise does not have a "simple continental crustal structure".

The tectonic history of the "Lord Howe Rise-Fairway Ridge"complex near the 23°S Transition Zone can be summarised in four main phases:

- the early-to-middle Cretaceous, a time of extension (rifting) and breakup of the eastern margin of Gondwanaland;
- the late Cretaceous - middle Eocene, a time of spreading with the opening of the Tasman Sea along a NNW-SSE trending spreading axis with associated NE-SW transform faults;
- the late Eocene - early Oligocene, was dominated by the thrusting of the ophiolitic belt over the New Caledonia basement, this provoking crustal shortening with associated overfolds and overthrusts, and formation of structural features that were pushed up during the collision phase to form the Lord Howe Rise - Fairway Ridge structural complex. The compressive event and the crustal shortening took place along N50°-60°E trending transcurrent faults, probably inherited from transform faults associated with the former spreading system of the Tasman Sea, and which are used again as right-lateral faults. This compressive event produced distortion of the overlying sediments;
- and the early Oligocene to Recent, which was a time of sediment deposition in the structural basins and non-deposition on ridges.

In the south, near 33°S, the Wanganella Ridge overthrusts the West Norfolk Ridge (Eade, 1988). We interpret the Wanganella Ridge and the two lateral troughs that bound it to represent the southern extension of the New Caledonia Basin, and the Fairway and the West Norfolk Ridges to be the northern and southern parts of the same feature.

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# NEW CONSTRAINTS ON THE PERMIAN TO EOCENE TECTONICS OF THE SW PACIFIC: EVIDENCE FROM NEW CALEDONIA

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The geology of New Caledonia records three major plate tectonic events; island-arc convergent margin tectonics from the Permian to the latest Jurassic culminating in a major accretion and obduction event in the earliest Cretaceous, mid Cretaceous to early Eocene passive margin extensional tectonics, and mid Eocene to Oligocene convergent margin tectonics.

The Pre-Cretaceous geology belongs to one of three arc-related terranes. The Boghen terrane is an undated, regionally metamorphosed arc-related sequence of deformed volcanics and sediments in the central part of the island. The Central Chain terrane is an Early Triassic to Jurassic marginal basin which includes a basal ophiolite with boninitic volcanics overlain by a thick volcaniclastic sedimentary sequence. This terrane formed in an island arc-related system away from the Gondwana margin. The Teremba terrane outcrops on the mid western coast and contains late Permian calc-alkaline arc volcanics overlain by a thin sequence of shallow water pyroclastics and volcaniclastics of Triassic to Jurassic age.

Shortly after (10-30 m.y.) the accretion and obduction of the Pre-Cretaceous terranes to the Gondwana margin, subsidence associated deposition began in New Caledonia as a result of the opening of the Tasman Sea and the break-up of the eastern Australian margin. A thick deepening upwards sequence developed on the New Caledonian Platform. These sediments pass up section from Cretaceous sandstones interbedded with rift-related volcanics to Paleocene and Lower Eocene pelagic cherts and limestones. At this time New Caledonia was a thin submarine continental plateau surrounded by deep basin analogous to the present situation on the Lord Howe Rise. Passive subsidence of the platform was disturbed in the mid-Eocene by collision with an island-arc resulting in the emergence of the New Caledonia and the obduction of ophiolites. The collision occurred when oceanic crust located at a passive margin to the east of the platform was consumed in an easterly dipping subduction zone. During the last stage of subduction and the beginning of the collision part of the upper lithosphere of this passive margin basin was thrust over the platform. This first thin nappe, composed of basalts and dolerites with minor sediments, was quickly followed by the obduction of a thick section sub-arc upper mantle originally located in the upper plate of the subduction zone. This mantle sequence is presently 1500 m thick and contains harzburgite with minor dunite, pyroxenite cumulate gabbro and doleritic dykes above a serpentinised horizontal detachment.

Platform pelagic and passive margin sediments also involved in the obduction. Some were pushed ahead of the nappe and redeposited in a foredeep along with sediments from the erosion of the ophiolites. Others were overridden by the nappe and form thrust sheets below the main detachment. The dominance of basaltic and doleritic derived clast within foredeep sediments shows that they were deposited in front of the an ophiolitic nappe of basic volcanic origins rather than in front of the ophiolitic upper plate dominated by ultramafics.

During the obduction, part of the platform descended deep into the subduction zone resulting in eclogite facies metamorphism in the northern part of the island. The metamorphosed lithosphere was subsequently uplifted and unroofed as a metamorphic core complex in response to isostatic instability. Uplift of the north eastern part of the island may have caused the dense ophiolite nappe to slide further westward after initial obduction. Activity in the subduction/obduction zone ceased by the Oligocene. This fossil compressional margin now extends to the north along the d'Entrecastreaux Zone, to the south between the Norfolk Rise and the Loyalty Ridge and possibly the along the western side of the Three Kings ridge to northern New Zealand. Dredging and drilling of Eocene andesite seamounts along the South d'Entrecastreaux Ridge, the Loyalty Ridge and the Three Kings Ridge suggests that these were arcs associated with the convergent plate boundary described above. However, it is possible that they were also associated with westwards subduction at the beginning of the Tonga-Kermadec system after a flip subduction zone and the opening of the North Loyalty and South Fiji Basin as backarc basins, during and after the New Caledonian obduction events.

## MAGNITUDE AND TIMING OF NEW HEBRIDES ARC ROTATION FOLLOWING SPREADING PROPAGATION IN THE NORTH FIJI BASIN: PALAEOMAGNETIC EVIDENCE FROM NENDO, SOLOMON ISLANDS

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Anticlockwise rotation of the New Hebrides (Vanuatu) Arc during the late Miocene and Pliocene followed arc polarity reversal of the New Hebrides Arc - Vitaz Arc system, and was accompanied by spreading of the North Fiji Basin. Seafloor magnetic anomalies indicate that spreading propagated into the northwestern corner of the basin from an earlier spreading centre further southeast.

Nannofossil biostratigraphy, supported by magnetostratigraphy, indicate a late Gilbert Chron (about 3.5-4.1 Ma) age for the Malue Beds of Nendo, in the eastern outer islands of the Solomon Islands, at the northern end of the New Hebrides Arc. Palaeomagnetic poles from this formation indicates a total clockwise rotation of 50°±13°. Reversing this rotation, around a pole at a current "hinge" where the trends of the New Hebrides Arc and Vitiaz Arc/Trench meet, closes this corner of the North Fiji Basin. Hence propagation of spreading into the northwestern corner of the North Fiji Basin can be dated to after 3.5 Ma. Such an age matches a number of other significant tectonic events in the region, including a likely age for the cessation of subduction of the Pacific Plate along the Vitiaz and North Solomons trenches, and the 5-3 Ma age for the latest change in Pacific Plate motion.

An earlier palaeomagnetic study conducted in Vanuatu [Falvey, 1978] indicated a magnitude of about 24° for the rotation of the New Hebrides Arc associated with opening of the North Fiji Basin, and limited the initiation of this rotation to no earlier than 6 Ma. This rotation was to small to correspond to an opening around a pole near the "hinge" between the New Hebrides and Vitiaz arcs, and instead required a rotation pole further from the two arcs, introducing complexities to the New Hebrides/Vitiaz reconstruction. This result also appeared to conflict with magnetic anomaly ages of 8 Ma for seafloor in the North Fiji Basin. All samples older than 6 Ma from this earlier study were taken from the island of Malekula.

The 50±13° rotation recorded in Nendo is the right magnitude to reconstruct the entire arc (including the southern Vanuatu portion) to the Vitiaz Arc around a pole at the "hinge". The rotation in the northwestern corner did not commence until later, following the propagation of spreading into this region, but the northwestern segment of the arc is now aligned collinear with the Vanuatu section of the arc, so it seems that the rotation of the northwestern corner has "caught up" with Vanuatu section. There may be a dynamic control on this behaviour, to minimize deformation of the downgoing Pacific Plate. If this is the case, we can ascribe a total rotation for the whole arc, including the Vanuatu section, of about 50±13° (relative to the palaeomagnetic frame).

The discrepancy between this result and the earlier palaeomagnetic rotation may result from later local clockwise rotation of Malekula in response to collision of the arc with the D'Entrecasteaux Zone. This interpretation also shows the possibility that rotation of the Vanuatu part of the New Hebrides Arc began between about 10 and 8 Ma, coincident with the beginning of North Fiji Basin spreading. A new later Miocene reconstruction of the New Hebrides and Vitiaz arcs based on this interpretation requires a rotation of 39° around a pole on the Australian Plate close to the point of intersection of the two arcs (equal to a rotation of 43° relative to the palaeomagnetic frame). Further constraints from regional bathymetry, the Pacific-Australia relative motion vector, and the width of the offset between the Solomon Islands and New Hebrides arcs, together with kinematic models for Fiji and the Solomon Islands based on other palaeomagnetic studies, allow a late Miocene reconstruction of the broader Outer Melanesian Arc system (Solomons - Vitiaz - New Hebrides - Fiji - Lau - Tonga) to be proposed. The Fiji Platform is restored to a position in line with the New Hebrides Arc, a more satisfactory restoration than that derived from the earlier palaeomagnetic study in Vanuatu.

## THE RIFTING OF THE TONGA/LAU RIDGE AND FORMATION OF THE LAU BACKARC BASIN: THE EVIDENCE FROM SITE 840 ON THE TONGA RIDGE

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The tectono-sedimentary evolution of the southern Tonga Ridge during the latest Miocene to Pleistocene is described from seismic reflection profiles and drilling results from Site 840, located on the western margin of the Tonga Ridge. The evolution took place in three episodes which have been related to the rifting of the Tonga/Lau Ridge and spreading in the Lau Basin. Uplift of the Tonga Ridge in the latest Miocene is attributed to deformation caused by the rifting of the Tonga/Lau Ridge. The uplift confined sedimentation to the western side of the Tonga Ridge, although the (mainly volcanic) sediment sources remained unchanged from the Lau Ridge. A phase of minor flexuring and faulting in the early Pliocene precedes a period of effusive volcanism, during which depositional limits expanded. The volcanic source was again from the Lau Ridge and the volcanism is interpreted as taking place during a final rifting phase before the sundering of the Tonga/Lau Ridge. A further phase of minor flexuring in the early Pliocene is attributed to the sundering of the Tonga/Lau Ridge. Subsequent deposition on the Tonga Ridge takes place in isolation from the Lau Ridge. Late Pliocene volcanic sediments are sourced from the Tofua Arc, newly formed on the western margin of the Tonga Ridge.

## HMR1 SURVEY OF THE WESTERN WOODLARK BASIN, PNG

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A marine geophysical and HMR1 survey of the western Woodlark Basin captures the birth and evolution of an ocean basin only 3 m.y. old. The continental rifting to seafloor spreading transition involves both nucleation of discrete spreading cells and organized ridge propagation. Two ridge propagation events into the margin at 153°E formed continental slivers surrounded by oceanic crust. Spreading is about to propagate into this margin again. Rifting of the conjugate margins continues for ~1 m.y. after spreading has initiated between them. Extension does not immediately localize to the ridge axis, as shown by the present overlap between spreading and seismogenic margin faulting, and by inwardly curved

seafloor fabric and magnetic anomalies that require non-rigid reconstructions. The initial spreading system lacks transform faults and has both overlapping and orthogonally offset segments. It evolves by ridge propagation, ridge jumping, transform development, and ridge reorientation (the latter 0.1 Ma, after conjugate steps in the margins slid past one another along the Moresby Transform). An unusual zig-zag pattern of faulting along the reoriented ridge axes may be the result of an interplay between their former and present trends.

# THEME: Island and Basin Geology as a Framework for Resource Exploration

## RESULTS OF LEG 2 - SOPACMAPS CRUISE

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The SOPACMAPS 2 cruise was carried out onboard the RV "L'Atalante" from August 19th to September 16th between Honiara (Solomon Islands) and Suva (Fiji). The main objectives of the cruise were multibeam mapping and geophysical profiling in the EEZ of Solomon Islands as a part of an EEC-funded program coordinated by SOPAC. Five geological targets have been selected either for their geodynamic context or their economic potentialities: the New Georgia Sound within the main Solomon Islands is a sedimentary basin bounded by volcanic lines. It is interpreted as a pull-apart basin open in a left-lateral motion environment. Reefs edifices have been identified especially in the Iron Bottom Sound and could offer potentialities for oil investigation.

The East Malaita zone is located at the boundary between the North Solomon Trench and the Solomon Islands system. It shows deformation zones cut by recent post-subduction volcanism. The Melanesian arc gap is comprised between Vitiaz and San Cristobel trenches. It is composed of back-arc volcanic domain cut in a more recent phases by the probably active 9°30'S east-west trending ridge which represents the northwestern tip of the North Fiji Basin accretionary system.

The North New Hebrides area is located at the boundary of the volcanic New Hebrides province and the northern tip of the NFB oceanic crust. Active volcanism and faulting characterise the area. The Pandora Bank zone is constituted by large volcanic massives culminating at less than 500 m deep aligned on a roughly WSW-ENE direction, probably recently emplaced in the old oceanic crust of the NFB. In total, 6000 miles of profiles have been performed and 120,000 $km^2$ of the sea bottom has been covered. 133 maps have been drawn aboard in a quite real time.

## PETROLEUM PROVINCES OF THE SOLOMON ISLANDS

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Of the four southwest Pacific island countries recognised as having undeveloped petroleum potential, the Solomon islands is a country of superlatives. Of the four, it has the largest exclusive economic zone (1,340,000 $km^2$), the largest land area (29,800 km), and for petroleum evaluation purposes, the largest amount of seismic data (17,363 km). It also has the largest area of sedimentary deposition as measured within the outer 1,000 m isobath, and the greatest variety of structural and stratigraphic styles.

Unfortunately, the superlatives end there; although as in Fiji and Tonga, Tertiary reefs have been identified on offshore seismic, and there are a range of structural traps, some of the parameters of the petroleum potential probability equation are yet undetermined. Unlike Fiji and Tonga, no oil seeps have been identified and analysed. The only well drilled in the area was a shallow inconclusive test 150 km NW of the Shortlands in 1975. To date no good source rocks have been identified.

However, the island arc segments in Solomon Islands do contain major sedimentary basins covering over 66,000 $km^2$ with sediment thicknesses ranging up to 5,000 metres. Although the centre of these basins are in deep water (over 1,000 m), there remain areas amounting to over 17,300 $km^2$ with water depths less than 1,000 m occurring along the basin margins, making them attractive from the point of view of hydrocarbon production technology and economics.

The ultimate petroleum potential of the Solomon Islands can only be realised after additional detailed seismic surveys and substantive drilling by the oil industry confirms all the ingredients for economic reserves. In the meantime, the Secretariat is making a necessary major effort to upgrade the assessment of and promote the hydrocarbon potential. This includes a renewed source rock search, initiating a computerised stratigraphic database, and the migration processing of 2,541 km of older regional seismic data from six surveys in the shallow-water basin-margins of the Shortland, Russell, Indispensable, Malaita and Iron Bottom Basins This latter project was recently completed and resulted in significant presentational improvements which should enhance subsequent evaluations and also the value of The Solomons Islands data packages to the oil industry

On preliminary review of the data and previous work, the Solomons area can be subdivided into at least eight different petroleum provinces exhibiting four distinct structural and stratigraphic styles, and three types of reservoirs.

## USE OF COMPUTERS IN RESOURCE ASSESSMENT - AN EXAMPLE FROM SOLOMON ISLANDS IN HYDROCARBON EVALUATION

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The arrival this year of desktop computers in member countries, funded by the European Community (EC), has brought about a considerable increase in national capabilities to carry out resource assessments. SOPAC has held several training activities to instruct government scientific officers in the use of the computer power that is now at their fingertips. This paper reports on one such exercise: setting up a stratigraphic database and palaeo-geographic mapping in Solomon Islands.

The stratigraphic database has been set up on EXCEL. It integrates information from onshore geology and offshore seismostratigraphy. Following a thorough review of geological survey reports and maps, the onshore geology was summarised in twenty five stratigraphic columns, with information on age, formation name, thickness, lithology and environmental indicators. The seismostratigraphy of 18 representative regional seismic lines has also been studied to provide information on approximate age, thickness, seismic facies and environment. This information forms the basic stratigraphic framework of the database.

Information relevant to hydrocarbon evaluation was added to this basic framework, including in reservoirs, seals and source rocks. Information related to other resources can be added in a similar way.

The basic data was charted to produce scaled stratigraphic columns. These columns were imported to MS DRAW to produce stratigraphic correlation diagrams. A base map of the study area, generated by MAPINFO, was then used as a basis for plotting the stratigraphic columns and developing palaeo-geographic maps of different stratigraphic time intervals.

The stratigraphic database will be installed the desktop computer at the Geology Division in Honiara so that it can be further developed and updated by government geologists. Together with the mapping/drawing packages, the database provides a valuable tool for assessment other non-living resources, including minerals, aggregates and water, in addition to hydrocarbons.

## THE PACMANUS HYDROTHERMAL FIELD, BISMARCK SEA, PAPUA NEW GUINEA: AN UPDATE


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During the June 1993 PACMANUS-II cruise aboard RV "Franklin" we revisited the hydrothermal site discovered in 1991 by PACMANUS-I at Pual Ridge in the eastern Manus back-arc basin, conducting further CTD-hydrocast and towed camera-video surveys and collecting additional samples by dredge, grab and sediment corer.

Pual Ridge is one of eight major neo-volcanic edifices spread en-echelon along the East Manus Volcanic Zone (EMVZ) between the Djaul and Weitin transform faults (extensions of which crop out on New Britain and New Ireland). Its felsic volcanic affinity has been confirmed, with dacites predominant, andesites at deeper levels, and a new occurrence of rhyolite on the northeastern arm of this fork-shaped structure.

Massive sulfides were sampled by four dredges at the PACMANUS site. One haul yielded a mushroom-shaped chimney composed of cupriferous pyrite, covellite and bornite, which was associated with extensively altered dacitic hyaloclastite and some Fe-Mn oxide crusts. The other hauls, on fresh dacite lavas with conspicuous ferruginous staining along fracture surfaces, recovered a variety of fresh to partly weathered chimneys and mounds dominated by chalcopyrite and sphalerite-wurtzite. Ferruginous crusts were also recovered by grab at another portion of the deposit. Numerous cores and grab samples of bottom sediment were taken in the vicinity of PACMANUS to further examine geochemical anomalies arising from dispersal of plume particulates and to assess the recent history of volcanism and hydrothermal activity.

Camera-video tows recorded both inactive areas and active vents with abundant fauna, but did not significantly expand the size of the main PACMANUS field, the largest essentially continuous deposit within which is some 200 m across. However, a new zone of inactive chimneys, probably limited in extent, was found 4 km to the northeast. The hydrothermal plume above Pual Ridge was mapped in detail. Besides a bullseye anomaly close to PACMANUS it contains several other nodes, though separate sources for these were not identified in underlying camera-video tows.

Part of the PACMANUS-II cruise was devoted to exploring elsewhere in the eastern Manus Basin. Another dacite-andesite edifice (Yuam Ridge) directly east of Pual Ridge is heavily sedimented and apparently lacks hydrothermal activity. Two previously-unexplored neovolcanic edifices in the EMVZ further east from Pual and Yuam Ridges were established to be basaltic in nature. Several prominent fault scarps in sediment basins to either side of the EMVZ were also dredged, attempting to characterise the crust on which the neovolcanic edifices (including Pual Ridge) appear constructed. They returned relatively fresh pillow basalts and semi-lithified mudstones, thought to represent basement and cover sequences indicated from seismic data. At face value these results conflict with earlier suggestions that the eastern Manus Basin is underlain by thinned island arc crust equivalent to land exposures on New Ireland and the Gazelle Peninsula of New Britain, but it is possible we selectively sampled failed spreading centres associated with earlier back-arc extension.

A comparatively intense particulate and methane plume, apparently hydrothermal in origin, was discovered south of Bugave Ridge at the far eastern end of the EMVZ, 45 km east of PACMANUS. Its source was not located and requires further investigation. A CTD traverse across Tavui Caldera offshore Crater Peninsula near Rabaul found no evidence of hydrothermal activity.

The PACMANUS hydrothermal field at Pual Ridge is among the best modern analogues known for ancient volcanogenic massive sulfide orebodies hosted in felsic volcanic environments. It is now well surveyed by surface vessel techniques, and is a high priority target for manned submersible dives and possibly ODP drilling.

## MT KASI HIGH-SULPHIDATION ALTERATION AND GOLD MINERALIZATION, FIJI

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The Mt Kasi Prospect, which is located on Vanua Levu the second largest Island in the a Fiji Group, represents a structurally controlled style of high sulphidation alteration and gold/copper mineralization. Host rocks are Late Miocene lavas and pyroclastics which are intruded by dacite domes. Several centres of zoned alteration are localised at the intersection of cross faults with the more prominent members of the Mt Kasi Fault System (MKFS). Cross structures trend EW while the MKFS trends NNW as a series of parallel faults and shears with an inferred sinistral strike slip sense of movement. NW trending faults and breccias occupy dilational settings developed during the movement on the MKFS and form an en echelon pattern and local sigmoid shapes.

A two stage hydrothermal alteration event is envisaged in which the rapidly moving gas phase has produced several centres of zoned high sulphidation alteration ranging from cores of residual (vuggy) silica grading outward to silica alunite, pyrophyllite and kaolin alteration.

Gold and copper mineralization are associated with the fluid phase alteration which exploits the same plumbing system, following the gas phase. The competent and vuggy residual silica brecciates readily to host mineralization as the matrix to breccias and also filling pre existing voids. The grades of gold/copper mineralization are proportional to the matrix content of the breccias. Thus matrix-supported breccias proximal to the fluid upflow zones contain higher gold grades than the peripheral crackle breccias in the outflow zones. Unbrecciated residual silica alteration and the enclosing incompetent clay alteration are barren.

Subsurface geology defined using CSAMT geophysics and the existing drilling, have been combined with structure and alteration to delineate a fluid flow model for Mt Kasi. Several discrete alteration centres occur either side of an inferred main zone of fluid upflow adjacent to a dacite dome and these host locally oxidised gold mineralization.

# RESEARCH ACTIVITIES AT THE MARINE MINERALS TECHNOLOGY CENTER, UNIVERSITY OF HAWAII

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The Marine Minerals Technology Center (MMTC), Ocean Basins Division (OBD), at the University of Hawaii is approaching the start of its sixth year of operations. The program of research, technology development and education is multidisciplinary and international in scope.

During the first five years research at the OBD has been focused on tools and techniques for characterization of deep seabed metalliferous oxides, metalliferous sulfides and tropical carbonate sands with a lesser but long-term emphasis on potential minerals development and related environmental aspects. Greater emphasis is now being given to environmental matters. Specific projects in research and technology development supported by the Center have included:

- Advanced design for a deep seabed gramma measurement data collection system
- Computer aided design methodology for power, communication and strength umbilicals for ROVs
- Development of a free-fall seafloor hard substrate corer
- Microtopography of manganese crust deposits
- Evaluation of the cobalt crust continuum on seamounts in the exclusive economic zone of Hawaii
- Characterization of a cobalt-rich deposit in the Johnston Island exclusive economic zone
- Quantitative determination of seabed microtopography
- Maximizing the returns from twenty years of deep seabed mineral exploration (by analyses of environmental data)
- Detailed analysis of the origin and distribution of platinum in manganese crusts
- Technology development for characterization of ree sand deposits
- Characterization and environmental impact assessment of tropical ref-derived sands for beach replenishment
- Geochemical characterization of manganese nodules from the Clarion-Clipperton zone
- Investigations into the use of manganese nodules as a regenerable hot-gas desulfurization sorbent
- Utilization of advanced technology for the characterization of marine mineral deposits
- Geothermal scientific observation hole program
- Geochemical characterization of the OMCO manganese nodules from the Clarion-Clipperton Fracture of the Pacific
- Underwater gravity separation and hydraulic classification of ocean minerals
- Evaluation of the suitability of a coarse-grained hydraulic bucket sampler for marine placer deposits and mine tailings site
- Shallow submarine hydrothermal systems and their mineral potential in the SW Pacific

Reports on these projects are available on request.

The Ocean Basins Division also has a serious commitment to the transfer of marine minerals technology through conferences, teaching and training. Conferences supported have included a workshop on Marine Mining Technology for the XXIst Century; the 19th, 20th and 21st Underwater Mining Institutes; Stockpile 2000 on the technology for the development of marine strategic minerals; and an Annual MMTC Seminar in Honolulu or the mainland.

OBD staff and faculty teach graduate division classes in Ocean Minerals, Marine Mining

Systems, Environmental Effects of Deepsea Mining, and Geothermal Systems for Small Islands. International workshops or short course have been held in Hawaii with the United Nations and US Geological Survey and in PR China with the State Oceanic Administration, the China Ocean Minerals Research and Development Association (COMBRA), and the Ministry of Geology and Mineral Resources

The acquisition and storage of unique sample and data sets from members of the deep seabed mining industry has resulted in exchange opportunities with other organizations to develop techniques for exploration and mitigation of environmental effects. The Center is the repository for one of the most complete collections of data and information on marine minerals and mining in the U.S.

In 1993, on the basis of the Center's activities, the University of Hawaii was designated by the U.S. Department of the Interior as the State of Hawaii Mining and Mineral Resources Research Institute.

## PRELIMINARY RESULTS OF SOPACMAPS CRUISE (LEG 1)

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The SOPACMAPS Project, funded by the EEC, has been awarded to IFREMER by SOPAC. It consists in mapping areas of the seafloor of Fiji, Solomon Islands, Tuvalu and Vanuatu using the RV "L'Atalante", a 85 m ship launched in 1990, specifically designed for swath mapping. She carries a dual SIMRAD EM12 multibeam echo-sounder giving both bathymetry and acoustic imagery over a swath width of up to 7 times the water depth. In addition, geophysical data are acquired continuously (gravity, magnetism, sediment penetration and quick seismic reflection).

The first leg (Leg 1) started from Nouméa (New Caledonia) on the 18th July 1993 and ended in Honiara (Solomon Islands) on the 15th August. During this leg, 11,260 km were run at the speed of 10 knots and the data continuously recorded. The areas covered lay in the Solomon Islands and Vanutatu waters:

- Central basins of the New Hebrides island arc: North and South Aoba Basins, Big Bay Basin, and partially the Banks Basin
- North New Hebrides Back-Arc Area: a zone east of the Santa Cruz (Solomon Islands)
- southern part of the "Melanesian arc Gap", a zone lying north of the San Cristobel trench between the Santa Cruz islands and Makira (San Cristobel) island
- parts of the Indispensable Basin bounded by Makira, Malaita, Santa Isabel, Nggela and Guadalcanal

## THE GEOLOGY AND MINERALISATION OF THE WAISOI PORPHYRY COPPER DEPOSIT, FIJI

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Mineralisation has been known in the Namosi area since 1857. Work by the Mineral Resources Department in the early 1960's encouraged exploration which resulted in the discovery and initial evaluation of the porphyry copper mineralisation at Waisoi. This resource was estimated as 590 million tonnes grading 0.47 % Cu and 0.15 g/t Au (0.3 % Cu cut-off) in 1980 (re-estimated as 590 million tonnes of 0.45 % Cu and 0.15 g/t Au in 1991).

Additional drilling during 1992 by Placer resulted in the development of a revised model of the geology, alteration and mineralisation within the interconnected deposits at Waisoi East, Waisoi West and Waisoi North.

Wainamala Group greenschist facies basaltic volcanics form the basement stratigraphy at Waisoi, and are overlain by the volcano-sedimentary Basal Namosi Conglomerate unit. This 30-50 metre thick unit is composed of reworked Wainamala/Colo basement, mixed with later Namosi Andesite material. Overlying this local marker unit are the devitrified calc-alkaline Namosi Andesite volcanics. These three units have been intruded by high level porphyritic dacite stocks and dykes, similar in composition to the Namosi Andesite lavas. Korobasabasga Pyroclastics post date the intrusives and form the ridges around the Waisoi valley.

Copper-gold-molybdenum mineralisation is hosted primarily by the porphyry stocks plus the enclosing Wainimala volcanics and Basal Namosi Conglomerate units. The earliest non-mineralised porphyries intruded along a NE structural trend while later mineralised porphyries intruded along NE and NW trends. Compression, dilation and intrusion of the porphyries has resulted in extensive brecciation of the host rocks allowing mineralisation along fractures, particularly the brecciated main intrusives/country rock margins where stockworks are developed.

Later N-S and E-W block faulting has significantly affected the Waisoi East deposit. Higher grade mineralisation in Wainamala Agglomerate is preserved in the down thrown eastern block but eroded from the uplifted western block, where an annulus of mineralisation occurs around the low grade siliceous porphyry intrusive core. The Waisoi West deposit is more completely preserved with weakly mineralised Namosi Andesite forming much of the overburden.

The Waisoi mineralisation is contained within a large hydrothermal system which affects an area of approximately 4 x 4 km. It is a low sulphur system with 0.2-2 % sulphur in the main ore zones and 2-5 % sulphur in the outer pyritic zones. This sulphide distribution produces a well defined chargeability response in regional Induced Polarisation surveys.

The 0.5-1.0 km wide outer propyllitic zone is characterised by a chlorite, silica, pyrite assemblage with later epidote and calcite sometimes evident. Pyrite generally ranges from 3-8 %.

The outer mineralised phyllic zone, characterised by chlorite, magnetite, biotite and sericite, has lower total sulphides (0.5-3 %). Chalcopyrite is the dominant sulphide with pyrite diminishing and bornite increasing inward.

The inner potassic and argillic zones are characterised by potassic feldspar, albite,sericite, quartz, clay, biotite and occasional corundum. Bornite is the dominant copper mineral.

Molybdenite occurs at deeper levels within the porphyry. Gold is most strongly associated with bornite/covellite but with some fine particulate gold in association with chalcopyrite/pyrite/quartz in stockworked areas. Accessory sulphides are sphalerite,tetrahedrite-tennantite and galena.

This alteration/mineralisation assembly produces a positive magnetic response over the outer mineralised zone where magnetite is associated with chalcopyrite/bornite. The mineralised central zone and non-mineralised outer propyllitic zones are magnetite deficient and show a low magnetic response.

The average depth of total oxidation at Waisoi is 30 m. In the south east of the Waisoi East deposit a limited zone of deep oxidation (100 m total oxidation) is located at the intersection of two major fault zones. At Waisoi West, two areas of deep oxidation are related to brecciation/faulting within or adjacent to intrusives.

No significant supergene mineralisation has been identified within the Waisoi deposits. Minor chalcocite occurs within the transition zone between oxidised and fresh mineralised units.

The current resource estimate based on the geological model developed from the 1992 drilling is 930 million tonnes grading 0.43 % Cu and 0.14 g/t Au (at 0.3 % Cu cut-off).

## RESULTS FROM THE AUSTRALIAN-SUPPORTED EVALUATION OF PETROLEUM POTENTIAL IN UNFASHIONABLE PHILIPPINES' BASINS: LESSONS FOR PETROLEUM EXPLORATION IN THE SOPAC REGION?

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Since 1992, the Australian Geological Survey Organisation (AGSO) and the Philippine Department of Energy (DOE), funded by the Australian International Development Assistance Bureau, have carried out a cooperative project to assess the petroleum potential of four frontier basin areas in the Philippines: Ragay Gulf, Tayabas Bay, Northeast Palawan and Cuyo Platform. New seismic data (2950 km) and direct hydrocarbon detection "sniffer" data (5000 km) were collected by using the AGSO's geoscientific vessel *Rig Seismic* and processed in AGSO. Onshore oil and gas seep samples were collected by DOE and analysed by AGSO. Australian and Filippino petroleum exploration companies are associated with the project.

Of the four survey areas, the Ragay Gulf basin of Luzon is of particular interest, with complex structures, multi-phase tectonism and thick sediment infill (maximum more than 7 km). It is aligned northwest-southeast, and is clearly a Tertiary, left-lateral strike-slip basin, formed by major splays off the Philippines Fault as a result of the collision of the Pacific and Southeast Asian Plates. Diapir-like structures (probably shale diapirs) are associated with the faults in places. The basin is formed in island-arc crust, and is about 80 km long and 15 km across, with the bulk of it offshore. There are numerous onshore seeps of oil from rich, mature source rocks on both sides of the basin, and exploration wells have had initial flows of up to 200 barrels/day.

The multichannel seismic data grid consists of 960 km of AGSO data and 2000 km of exploration company data, and the grid spacing is 2-5 km. The seismic interpretation has revealed the existence of five sedimentary sub-basins with 2.5-5 seconds (two-way time) of Eocene to Recent sediments. Several types of potential traps were documented, with the most prospective probably being buried carbonate platforms, buried atolls, and wrench-related structures.

Many geochemical "sniffer" anomalies were located in the gulf. These, together with $^{13}C$ and $^{14}C$ isotope analyses on the recovered (dominantly methane) gas have revealed the presence of significant source rocks. The seeps are thermogenic in origin, and the source rocks have reached sufficient maturity to generate significant quantities of hydrocarbons. Analyses of onshore oil and gas seep samples have indicated the presence of Early Tertiary source rocks of terrigenous origin, with mixed Type I and III kerogens. Most likely, they are sourced from fluvio-deltaic coaly sediments or calcareous shale, like other Southeast Asian source rocks. The geochemical data have been integrated with the seismic data to provide clues for hydrocarbon migration.

Overall, the Ragay Gulf clearly has encouraging oil and gas potential, and leases have been made available for bidding. The perceived potential of Ragay Gulf is substantiated by the following play attributes:

*Source*: Middle Miocene or older sediments as documented by the onshore drilling data, oil and gas seeps, and the geochemical "sniffer" data.

*Reservoir*: Late Oligocene to Early Miocene limestone or equivalents, and coarse clastics within the Middle Miocene formation.

*Migration*: Up-dip along stratigraphic paths and along non-sealing faults.

*Seal*: Shales and other fine clastics within the Middle Miocene or younger formations.

*Traps*: Carbonate reef build-ups, unconformity traps, anticlinal traps, and wrench-induced block faults and folds.

A project of this type would clearly be considerable benefit to SOPAC countries in improving the assessments of petroleum potential already made with SOPAC help, and in generating additional company interest. In general, prospectivity along the Southwest Pacific island-arc is not rated highly, because of the paucity of commercial petroleum discoveries in similar terrains. Should there be commercial petroleum production from Ragay Gulf, or the adjacent Tayabas Bay, both of which are not unlike some Southwest Pacific basins, with their similar questions about source and reservoir rocks, the perceptions of prospectivity in Solomon Islands, Vanuatu, Fiji and Tonga could change considerably.

## GOLD MINING AT VATUKOULA, VITI LEVU, FIJI

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(no abstract received)

## RESULTS OF GEOCHEMICAL EXPLORATION OF THE SEAFLOOR OF PAPUA NEW GUINEA

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Geochemical exploration of the seafloor of Papua New Guinea has been carried out as a part of Joint Basic Study for the development of Resources in the sea area of SOPAC (South Pacific Applied Geoscience Commission) of fiscal 1992. The purpose of the geochemical survey was to collect the fundamental data of chemical composition of deep sea sediments in order to acquire the guidance of exploration for the seafloor hydrothermal mineralization.

The geochemical sampling consisted of wide-range regional sampling, base line sampling and sampling in the mineralized zone. The bottom sediments were collected from 88 points and were used for chemical analysis (250 specimens) and powder X-ray diffraction analysis (200 specimens).

(1) The mineralized zone was identified by a continuous deep sea TV camera (FDC). The maximum length of the 5 mineralized zones was 550 m along the track line and the minimum length was 30 m. They consisted of yellow to red brown precipitates and about 3.2 tonne of them was collected.

The precipitates consisted mainly of $SiO_2$ and Fe, and content of sulfur was less than 0.2 %. As a result of powder X-ray diffraction analyser, the precipitates consisted mainly of amorphous minerals accompanying montmorillonite. The quantity of zeolite, chlorite, sericite, sericite/montmorillonite mixed layered mineral, gypsum and pyrite was less than that of the regional samples.

(2) Comparing the mean values of $Fe_2O_3$, As, Mo, REE, $P_2O_5$ and P in the mineralized zone to those of the regional samples, they were significantly enriched while CaO and Ni content were depleted.

| | main positive factor loading | main negative factor loading |
|---|---|---|
| 1st comp | CaO(0.91), LOI(0.90), Sr(0.69) | $Al_2O_3$(-0.92), Ga(-0.88), $SiO_2$(-0.79), $K_2O$(-0.71), MgO(-0.67), FeO(-0.67), $TiO_2$(-0.64), Cu(-0.60), T-$R_2O_3$(-0.56) |
| 2nd comp | Zn(0.82), Sb(0.79), Ni(0.74), S(0.68), MgO(0.51) | $SiO_2$(-0.44) |
| 3rd comp | Cu(0.34), Co(0.34) | As(-0.76), Mo(-0.74), $Fe_2O_3$(-0.71), P(-0.66), $Na_2O$(-0.37) |
| 4th comp | Hg(0.69), Cl(0.62), $Na_2O$(0.52), Mn(0.44) | $TiO_2$(-0.47), FeO(-0.43) |

(3) Sea bottom sediments in this area can be classified into 5 types by their color and the color and chemical composition of the sediments show the following obvious relation:

- Red brown sediment was collected from only near the mineralized zone and it was characterized by the abundance of the oxides and elements such as $Fe_2O_3$, $P_2O_5$, As, Sb, Mo, Total rare earth elements (REE) and P.
- Brown sediment was characterized by the abundant MnO, Mn and Hg.
- Olive to gray sediments contained abundant CaO, LOI, Ag and Sr, and showed ample content of foraminiferal fossils.
- Black sediments was characterized by $TiO_2$, FeO, Ni, Cu, Co, Zn and Ga.
- White sediment consisting mainly of $SiO_2$, $Na_2O$ and $K_2O$.

(4) From the result of chemical analysis and powder X-ray diffraction analysis using the regional samples of seafloor surface, a pattern of distribution of mineral assemblage and characteristic chemical composition was recognized to coincide to large scale bathymetric features, such as plateau or basin, and showed the place where it was suitable or not for the sedimentation of clastics and volcanic materials from land.

For example, alteration minerals such as zeolite, chlorite, sericite/montmorillonite mixed layered minerals together with quartz and plagioclase were dominantly distributed in New Guinea basin, and the sediments in the area contained abundant silica. On the other hand, calcite and aragonite derived from foraminiferal fossils were dominantly distributed in the northern shallow sea of the survey area and the sediments were CaO rich.

(5) Values of $Fe_2O_3$ of the sediments collected from the surface of seafloor along the two base line showed the increasing trend towards the spreading center which was inferred topographic features and the result of magnetic survey.

(6) The result of Principal Component Analysis based on Correlation Matrix, using 29 components of oxides or elements, are summarized in the table below. The 3rd component is considered to show one related to the mineralized zone.

(7) The mineral composition in the mineralized zone, which were observed under the microscope, will be also presented.

## VARIATIONS IN TYPES OF GEOTHERMAL SYSTEM WITH GEOLOGICAL SETTING AROUND THE PACIFIC RIM

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The nature of magmatic-related geothermal systems varies systematically with their geological setting. The geological setting affects the volcano-tectonic characteristics of the areas which, in turn, affects the chemistry and hydrology of the geothermal systems occurring there. Thus, models developed in, say, a continental setting may not be readily applicable in an island arc setting. This can lead to difficulties in exploration for geothermal energy, but it can also be a powerful tool to apply when developing predictive exploration models.

Epithermal and porphyry-related gold and base metal deposits are the fossil equivalents of active geothermal systems. Applying the appropriate mineralisation model, based on the geological setting, is therefore essential when attempting mineral exploration based on paleo-hydrological reconstruction of the mineralising hydrothermal system.

## GROUNDWATER RESOURCES IN FIJI

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The Mineral Resources Department (MRD) is responsible for the collecting and storing all information relating to groundwater in Fiji. Investigations and research carried out by the Hydrogeology Section of MRD are aimed to improve knowledge of groundwater and are directed to areas of particular need so that groundwater could be utilized quickly. A wide range of equipment and techniques are used to locate and assess groundwater resources, including drilling of test and production boreholes by the Drilling Section of MRD which has several drilling rigs to carry out diverse drilling operations in all geological conditions. Detailed groundwater investigations are funded by MRD, PWD (Water Supply) for urban and rural water supplies and by MPI for irrigation schemes.

A small section of Fiji's reticulated supply comes from groundwater. However, the situation is changing as knowledge of groundwater resources grows and groundwater is beginning to be regarded as a viable option in more and more cases.

In rural situations, especially on small islands, groundwater is used conjuctively with roof catchments and surface sources (eg. Lakeba, Vanua Balavu, Dravuni). Boreholes for water supply have been drilled by MRD on Naviti (Yasawas) and Galoa (Kadavu) and these will be used for village water supply in the near future. Groundwater investigations of selected islands in the Yasawa, Macuata, Lomaiviti and the Lau Groups have been undertaken. Visit to selected islands in the southern Lau Group was also undertaken.

The major demand areas of the larger islands are located on the drier sides on the where supply cannot be guaranteed throughout the year (eg. north Viti Levu, southern Taveuni). Demand for additional water supply is increasing in the urban areas where supplementary supplies to the existing schemes are required to meet the new demand (eg. Labasa, Ba, Sigatoka, Navua). There are existing production boreholes in Labasa, Ba, and Sigatoka, and production borehole for Navua/Deuba region has already been drilled by MRD.

The use of groundwater for irrigation of cash crops is growing (eg. Legalega, SVRD project in the Sigatoka Valley). In addition, the growth of tourism has major implications in the field of water supply (eg. for the Natadola Tourism Development Project where groundwater may be the least costly option).

Groundwater resources are fragile and finite, hence it is necessary not only to find ways of removing it from storage but also to assess the volume and quality of the resource. The Mineral Resource Department through its Hydrogeology Section continues to monitor, assess and develop the groundwater resources of Fiji.

## GEOLOGY OF AMANAB, PAPUA NEW GUINEA

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(no abstract received)

## GEOTHERMAL DEVELOPMENT POTENTIAL OF THE PACIFIC ISLAND NATIONS SITUATED ALONG THE PACIFIC "RING OF FIRE"

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Geothermal energy has a great potential for meeting the electrical and thermal energy requirements of many countries lying along tectonically active zones within and surrounding the Pacific Basin. Energy requirements for many of the small, scattered island nations preclude development of conventional generating facilities large enough to incorporate many economies of scale. However, by attempting to discover and develop shallow, relatively low temperature, geothermal reservoirs associated with recent volcanism on many of these island nations, exploration expenditures and risks, and problems associated with the development of high temperature resources can be reduced. Exploration and development drilling for these resources can be accomplished with truck mounted rotary drilling rigs that are less costly and more suitable for operation within the island infrastructures than the conventional rigs normally used in the drilling of deep, high-temperature geothermal resources.

Experience over the past decade with small, modular, binary (Rankine) cycle generating units indicates that geothermal energy can provide a reliable source of baseload electricity in the amounts required and at a cost that is competitive with other alternative energy sources. Development of shallow, moderate temperature, geothermal resources with small, modular, generating units can provide ideal additions to the energy sources of many of the Pacific island nations within the framework of their island economics.

## STRUCTURAL EVOLUTION OF THE AURE FOLD BELT, OFFSHORE PAPUA NEW GUINEA: IMPLICATIONS FOR HYDROCARBON POTENTIAL

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The Aure Fold Belt forms an extension of the Papuan Fold Belt in the western Gulf of Papua. Whilst all PNG's commercial oil and gas discoveries to date have been found in the Papuan Fold Belt, numerous oil gas shows in wells and gas seeps at surface indicate that the Aure Fold Belt also has hydrocarbon potential. However, drilling so far has been unsuccessful owing to incorrect seismic interpretations of the complex structures. There is also uncertainty regarding the timing of the structures relative to oil and gas generation.

This study has determined the structural style by constructing balanced and restored sections based on seismic data. This is the first time this advanced technique has been applied to the Aure Fold Belt. The results show that fold belt results from thin-skinned deformation with detachment at the base of the Tertiary and involves a Tertiary cover up to 8 km thick. Deformation occurred in a hinterland to foreland sequence as result of the collision of the Melanesian Arc with the Papuan foreland. This resulted in around 25% shortening of the cover in one main phase, commencing at about 6 to 7 Ma The major structures are large scale thrusted anticlines which had formed principally by 2-3 Ma. There is also evidence of a late reactivation of some thrusts which intersect the seafloor.

The main source rocks in the Tertiary succession are Palaeogene Moogli Mudstone and the Neogene Chiria Formation. Kerogen Type III is dominant and the source rocks are consequently gas-generative. Computer modelling indicates that the main kitchens are in the footwalls of the major thrusts. The top of the oil window is predicted at 4 km depth. Oil generation occurred within the last 5 Ma. Reservoirs occur in the Talama Formation (Upper Miocene) and the fractured Karuku Limestone (Neogene).

Using balanced sections as a basis for structural mapping, several prospective traps have been identified. These include four way dip closures and faulted dip closures, both in hanging wall anticlines. Typical trap areas are $45 km^2$ with vertical closures of up to 400 m. The traps are either contemporaneous with, or post-date hydrocarbon generation, and thus exhibit favourable timing of trap formation relative to oil and gas migration.

## SOUTH PACIFIC PETROLEUM SURVEY - A MAJOR NEW INITIATIVE FOR EXPLORATION OF THE REGION'S OIL AND GAS RESOURCES

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Fiji, Solomon Islands, Tonga and Vanuatu represent a frontier area for hydrocarbon exploration. With only 13 wells drilled and 60,000 km of seismic data acquired, this vast region of the South Pacific is under explored. Preliminary evaluations have been carried out by SOPAC which integrate all available data. These studies have revealed many encouraging indications, including oil seeps (Tonga and Fiji), source rocks capable of generating hydrocarbons (Fiji, Vanuatu and Solomon Islands), Tertiary reef reservoirs throughout the region and several areas with potential traps (Fiji, Tonga and Solomon Islands). Preliminary economic analysis of these prospects indicate that they may hold commercial reserves of oil and gas. Based on this evidence, several shallow water areas have been highlighted which are thought to have the best potential for hydrocarbon prospects.

However, more comprehensive hydrocarbon evaluations are hindered at present because the existing seismic data in most areas are either too sparse or of poor quality. As a result it may not be possible to attract international oil companies to invest in exploration drilling since the perceived geological risks are too high. This is critical because future development of the region's petroleum resources hinges on substantial industry investment.

Consequently, at the Governments' request, a project proposal has been produced for a major new seismic survey of selected offshore areas of Fiji, Solomon Islands, Tonga and Vanuatu. The total project cost is about F$15.5 million over four years. The project is divided in three stages:

(i) acquisition of 10,300 km of high quality seismic and other geophysical data;

(ii) computer processing and interpretation of the seismic data which will improve the geological knowledge of the petroleum prospects of the selected areas; and

(iii) presentation of the data and results of the survey to the international oil industry in order to encourage investment in exploration.

Training of member country nationals plays a major role in all stages of the project so as to build Government capacities in petroleum resource assessment and management.

The project proposal has been completed in consultation with member countries. In view of the size of the project, funding will be sought from a number of sources, including international aid donors, oil companies and industry contractors. As with the earlier successful Tripartite program, SOPAC will also seek the support and collaboration of other government agencies and research institutes.

## PAPUA NEW GUINEA GEOLOGICAL AND EARTH RESOURCES INFORMATION SYSTEM: 'GERIS'

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In 1987, the PNG Department of Mining and Petroleum, principally through the Geological Survey Division, began a program to develop and maintain a system of integrated titles management and geoscience databases. The computerized database system that was developed is known as PNG GERIS (PNG Geological and Earth Resources Information System).

GERIS is a collection of corporate databases designed to be used with commercial Geographic Information System (GIS) software, such as ARC/INFO or MAPINFO, to allow rapid search and analysis of a wide variety of spatially referenced geological/geophysical attribute data and mineral resources information for PNG. To maximise access to the databases, they are maintained as master copies on a 486-based PC using the XENIX multiuser operating system. The databases can be accessed in text form from either Wyse 60 terminals or PCs connected to the XENIX network. By using low-cost PC hardware and commercial software, capital and operating costs have been minimised. A similar system could be set up for about $US30,000.

Figure 1 shows the existing and planned databases that make up GERIS with lines showing the links between the various databases. The status of the database system is summarised in Table 1. Other spatial databases exist in the Department, for example the Petroleum Licence databases maintained by the Petroleum Division and the seismic databases held at the Geophysical Observatory, but these are currently not a part of GERIS.

Table 1.

| DATABASE | INFORMATION | STATUS | NUMBER OF RECORDS |
|---|---|---|---|
| BIBLI | Bibliographic details for reports held in the GSPNG archive | Active, copies available to public | >12,000 |
| BIBLI_DOC | Location data showing area coverage for each report in the Bibliographic database | Active | >500 |
| Mineral Licence | Stores details of all Minerals exploration Licences since 1987 | Active | All active exploration licences |
| MINOCCUR | Geological and production details on mineral occurrences throughout PNG | Active, not yet available to public | >700 |
| COAL | Geological and Publication details for all coal occurrences throughout PNG | Awaiting data entry and checking | >300 |
| SAMPLOC | Stores location data for all sample databases | Awaiting data entry and checking | >1,000 |
| ISODATE, PETROKEM, PALAEO | Reference databases with information on isotopic dating, rock geochemistry and palaeontology | Awaiting data entry and checking | >1,000 |
| EXPLORKEM | Stream sediment geochemistry from GSPNG stream sediment sampling work | Data in digital form awaiting finalised version of database | >3,000 |
| VOLCANO | ? | ? | ? |
| SLIP | Details about the size and geology of landslides on the Markham 1:250000 sheet | being developed | |
| STRUCT | Structural Production | Planned | |
| MIN_PROD | Mining Production | Planned | |
| STRATIG | Straigraphic Authority database will include information such as unit names, ages and lithology | Planned | |

The first databases developed for GERIS were those essential to the administration of mining tenements and accessing the Department's library of unpublished reports and publications. These databases (PNG BIBLI and several mineral licence management databases) are mature and stable, requiring only routine updating.

These databases have greatly reduced the time needed to administer the 150 current minerals tenements. For example it takes only four man hours per week to keep the biannual prospecting and expenditure database up to date and to ensure all companies are up to date with their reporting requirements. Without these databases this task could occupy at least 12 hours a week of a senior officer's time. The Department has also been producing minerals tenement maps using GERIS since 1987.

Existing databases have been designed to conform to a relational model. In common with geoscience databases developed by other organisations, GERIS databases containing specific information about mineral occurrences and rock, stream sediment or soil samples are referenced to a site location database. The site location database contains all the information needed to describe the location of the site, the method used to locate the site and positional accuracy.

Text information in the databases is generally limited to descriptive terms chosen from data dictionaries developed for each field by GSPNG geologists. Much of the development time for the databases has gone into devising data dictionaries. In creating data dictionaries, a deliberate decision to avoid the use of codes and lookup tables was made. It was felt that this has several advantages. Codes can make databases seem cryptic and thus may discourage some geologists from using the databases. It was also found that it is easier to identify errors in databases where entries are written out in full. Finally, by not using codes or abbreviations, the need to supply a copy of the codes and look up tables when transferring copies of the database to outside customers was eliminated.

An additional relationship for GERIS databases is the linkage of geoscience attribute databases to PNG BIBLI. Use of the unique GSPNG Archive Report Number as the reference for each data record allows a user to easily check an original reference.

Mineral occurrence, coal occurrence and stream sediment geochemistry databases (MINOCUR, COALOCUR, EXPLORKEM) of immediate use to the minerals industry are currently being checked prior to their release to the public. These databases should be a valuable contribution to minerals exploration in PNG. They will allow immediate production of new and custom maps critical for resource area evaluation.

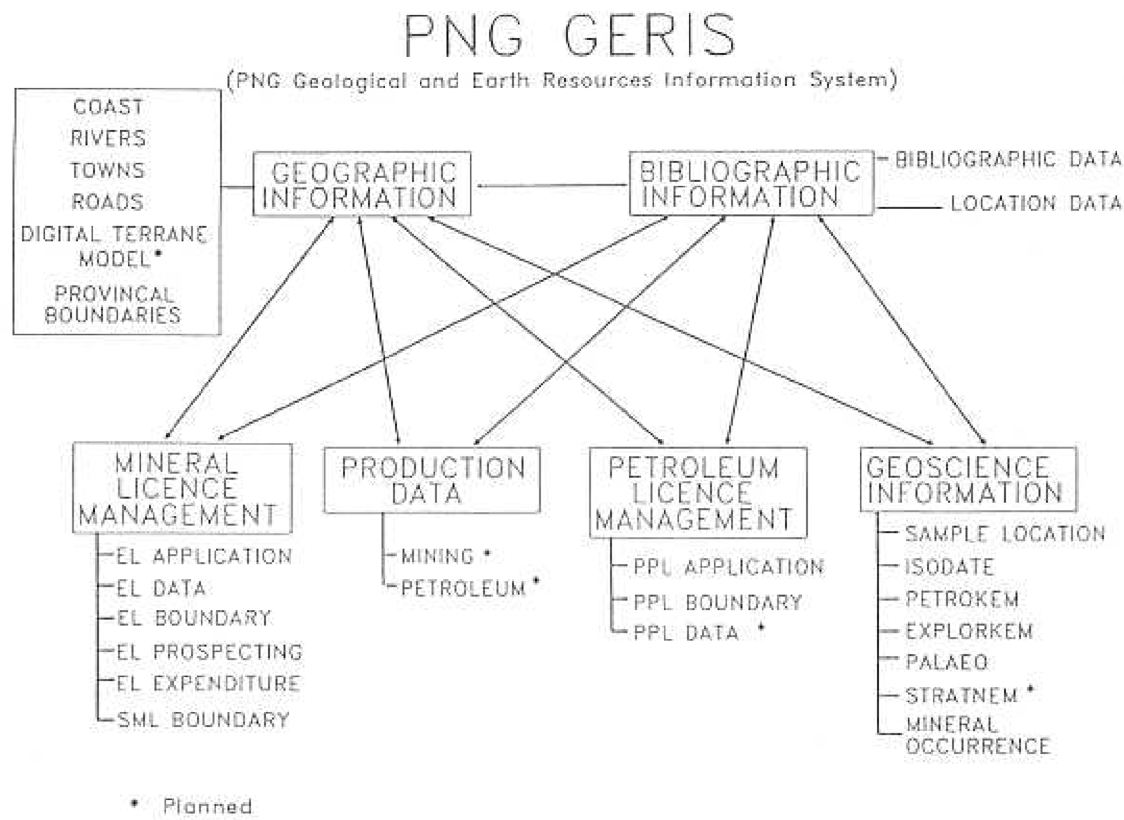


*Figure 1. Links between the various databases within GERIS.*

Regional geoscience attribute databases are the latest area of development. These databases (SAMPLOCAT, ISODATE, PETRO, PALAEO, STRATA, STRUCTURE, LANDSLIDE, LINEAMENT, HYDRO) are at different stages of development, data gathering and checking. All, except STRATA, are scheduled to be fully operational by the end of 1994. The geoscience mapping databases will store the essential field data that will be used to make the second generation geoscientific maps for PNG.

Essential to GERIS are the geographic data which will allow useful maps to be made from the attribute databases. Work is currently under way to capture as digital coverage the existing 1:100,000 and 1:50,000 geological maps. All new geological mapping will be digitised into this system.

Topographic base information such as drainage, culture and shore lines are the responsibility of the National Mapping Bureau of the Department of Lands. National Mapping is currently working towards production of the first digital topographic maps for PNG.

Ultimately, the databases will be combined and analysed with the assistance of GIS software to produce maps showing such information as landslide hazards, mineral and petroleum potential, groundwater quality and environmental hazards.

# THE PAPUAN ULTRAMAFIC BELT ARC COMPLEX

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The Papuan Ultramafic Belt (PUB) is the best known marine volcanic unit in Papua New Guinea and is considered a type ophiolite. The northeastern side of the Papuan Peninsula contains elements of the PUB and the Owen Stanley Metamorphics (Kagi Metamorphics), separated by the Owen Stanley-Timeno Fault Zone.

The Kagi Metamorphics consist of grey, carbonaceous, partly calcareous, mica schists, some of which contain epidote, lawsonite and blue amphibole. Blue amphibole-epidote-lawsonite-garnet meta-basic pods occur in the Owen Stanley Fault Zone. Conventional K/Ar isotopic ages on glaucophane and muscovite, from metamorphics occurring within a relatively small area, form a spectrum ranging from 45-22 Ma. We interpret these ages to suggest that recrystallisation of these high P/T metamorphics occurred during a subduction event beginning in the Late Eocene and ending with collision of the Owen Stanley Metamorphics and the PUB in earliest Miocene times.

Elements of the PUB, the Eia beds and the lower part of the Cape Vogel Basin constitute the Bowutu terrane. The PUB consists of a basal ultramafic layer of variably serpentinised, foliated websterite and lherzolite and rare dunite pods, intruded in part by gabbro. Most ultramafic rocks are tectonised, and the dominant composition is harzburgite. Olivine compositions are $Fo_{92-94}$, orthopyroxene $En_{92-94}$ and chrome spinels have (Cr/(Cr+ Al)) ratios around 0.9. When these olivine, chromite and orthopyroxene data are plotted along with mineral composition data for other ophiolites, the PUB falls within a group of ophiolites interpreted to preserve primitive island arc crust and upper mantle.

Overlying this layer is a zone of variably foliated gabbro/dolerite. Pillowed and massive spilitic basalt (Lokanu Volcanics) overlies the gabbro and is almost horizontal in many areas. Whole-rock geochemical data show that the basalts are tholeiitic ferrobasalts, with flat 5 x primitive mantle REE abundances. Overlying the basalt in the lower Waria River area is a thin, laminated hemipelagic maroon micrite containing planktic foraminiferids yielding a P4 assemblage. We thus assign this age (Late Paleocene) to the Lokanu Volcanics and hence the PUB superstructure.

Hemipelagic sedimentation was superseded by coarser volcanolithic sediments of the Eia beds, which overlie the Lokanu Volcanics. Stratigraphic relationships between the two units are unclear, but it is possible that an angular discordance is locally present. The Eia beds consist of medium to thick bedded volcanolithic sandstone and conglomerate, calcareous siltstone and cream-buff micrite, and variably altered basaltic, andesitic-dacitic and rarer rhyolitic lavas and breccias.

Foraminiferids indicating an upper P5-P16 age, and a hornblende K/Ar age of 47 Ma (Early Eocene) from a dacite lava, have been obtained from the unit.

Intruding both the gabbro and Lokanu Volcanics of the PUB, and the Eia beds, is a distinct suite of hornblende-bearing trondhjemite, tonalite, diorite and porphyritic dacite stocks with K/Ar ages ranging from 57-51 Ma. Geochemically, the intrusives have low LIL element, low high-field strength cation, and low (1.5 x primitive mantle) REE abundances. Both the age and geochemical data confirm earlier work suggesting the Eia beds and these dioritic-dacitic intrusives are co-magmatic.

The Iauga Volcanics, basement to the Cape Vogel Basin, consists of variably altered, feldspar-phyric, andesitic-dacite-rhyolitic lavas, volcanolithic breccias and conglomerate, volcanolithic sandstones and siltstones, and rare biomicrite. The boundary between the Iauga

Volcanics and the Eia beds has not been identified in the field. A foraminiferal assemblage recovered from a limestone lens near the presumed base of the unit yielded an Early to mid Oligocene age (Tc-Td). Thus, the age of the lower Iauga Volcanics is considerably older than the Late Oligocene ages previously assigned.

The Owen Stanley-Timeno Fault Zone reaches 7 km in width and marks the present boundary between the Owen Stanley and Bowutu terranes. Elements of both terranes occur within it. Maroon micrites, spilitic pillow lavas, gabbros and ultramafics are referable to the Bowutu terrane and green, slate-phyllite grade metamorphics originally formed part of the Owen Stanley Metamorphics. The tectonostratigraphic affinity of deformed, Late Cretaceous, laminated maroon and green micrites within the fault zone is unclear.

There are many mineral occurrences in the PUB, though the majority result from secondary processes. 'Syngenetic' lode deposits are limited to chromite seams in harzburgite/dunite exposed along the Paiawa River and in the headwaters of the Bonua River, the Doriri Creek nickel sulphide prospect and minor copper sulphide occurrences scattered throughout the PUB. Though the mineralisation at the Doriri Creek occurrence is hosted by hydrothermally altered peridotite, it is possible that the nickel sulphides were concentrated in the area prior to the hydrothermal activity.

Many of the secondary mineral deposits of the PUB are assumed to be formed by weathering of the ultramafic rocks or related mafic rocks. While this relationship is clear for the PUB nickel laterites (Lake Trist, Kokoda, Wowo Gap, Koreppa) the origin of the alluvial chromite and gold/platinum deposits is not straight forward. The alluvial chromite in the beach deposits of Hessan, Sachen and Buso Bays are presumed to be derived from disseminated chromite in the ultramafic rocks of the PUB.

While many of the streams that drain the PUB yield alluvial gold, it is difficult in most cases to prove that the PUB is the source of the gold. Much of the gold in the major tributaries is assumed to be shed from veins in the metamorphics and intrusives of the Owen Stanley Range. However, there are some auriferous drainages which cannot be explained by gold sources outside the PUB. Gold in rivers that drain the Bowutu Mountains (Wuwu, Wiwo, Mo, and Maiama) is shed from an area underlain by basalts and quartz diorite. Gold and platinum has been found in the Saia and Buso Rivers, which drain an area of gabbro and peridotite. The gold from the upper Gira River is believed to originate from plutonic rocks of the PUB or a fault slice of the marine basalts. Alluvial gold from the PUB is typically rounded, has a very high fineness (850-900) and does not tend to contain inclusions of other opaques (A. Wangu, personal communication).

Alluvial PGEs from the region are thought to be derived from the ultramafic rocks of the PUB. Other than the Lakekamu area, the Aikora and Gira Rivers and McLaughlins Creek are the only areas in PNG for which production of osmium and iridium are recorded. Rutheniridosmine, osiridium, laurite, isoferroplatinum and irarsite have been found in pan samples from the Aikora River area. No lode platinum occurrences are reported from the PUB.

On the basis of these field, geochemical and isotopic data, we postulate that the PUB consists of two overlapping units. The lower, tectonised ultramafics, undeformed layered ultramafics, cumulate gabbro, Late Paleocene MORB-like basalt and Late Paleocene hemipelagic sediments, represents some kind of oceanic, back arc or forearc crust and upper mantle as proposed by Davies (1971) and by many others since. However this crust was intruded by more arc-like, latest Paleocene-Eocene diorite/tonalite/gabbro and overlain by comagmatic ?arc basalts, ?forearc/arc andesites (including boninites) and dacites.

Reference

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# LIMESTONE GEOLOGY AND WATER RESOURCES IN GUAM AND IN THE COMMONWEALTH OF THE NORTHERN MARIANA ISLANDS

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A 500-meter thick composite section of Tertiary and Quaternary units comprise the principal aquifers on Guam and throughout Rota, Aguijan, Tinian and Saipan in the Commonwealth of the Northern Mariana Islands (CNMI). These units form a veneer on Eocene-to-Early Miocene volcanic basement basalts and andesites. Individual limestone formations represent a fairly complete sampling of the broad range of carbonate depositional environments from deep periplatform (Oligocene-Miocene) through reef margin to intertidal platform facies (Miocene-Pleistocene). Collectively, limestone units follow an overall shallowing-upward trend correspond with general emergence of the Mariana arc.

Productive water wells exploit basal and parabasal fresh water lenses that, on Guam, may reach a 100 meters in thickness, but average less than 40 meters of potable water. Exploratory strategies are generally guided by site accessibility represented on or inferred from 50 year old 1:50,000 bedrock geology maps. On Rota where no published map exists, the strategy for locating new wells is really one of proximity to water users. Increased pressures on the lens from developers on all islands but Aguijan (uninhabited) are necessitating stepped-up efforts to understand the dynamics of the individual aquifer system before too many new wells are pumping, to the long-term detriment of the entire lens system and economy.

Preliminary studies on northern Guam's "sole Source" aquifer over a decade ago showed that groundwater lens geometry, transmissivity, and sustainable yield are strongly influenced by basement configuration, structure, clay content, and proximity to coastal marine waters. A proposal to fine-tune this study, incorporating petrographic, structural geology, and additional geophysical studies, has been approved by the Guam Legislature and signed into law, but awaits funding from the Guam Environment Protection Agency. A major component of the study will also be the development of a mathematical model characterizing the northern Guam aquifer system. No comparable systematic geologic and geophysical study has been planned nor undertaken in the CNMI, although a U. S. Geological Survey modeling program is currently in its early stages on Saipan.

Limestones in the Mariana Islands have undergone two important types of transformations as a result of arc evolution: tectonic fracturing and geochemical-mineralogical diagenesis. Both have a profound on aquifer behavior, yet have had little impact to date on strategies of government water resource planners and managers or commercial developers. In combination, fracturing and diagenesis have developed porosity and permeability relationships within the aquifers that are virtually independent of depositional facies and previously mapped stratigraphy.

Fracturing occurs as kilometer-scale faults and breccia zones, together with smaller faults, offsets, and well organised joints. Many faults conform to theoretical directions of principal crustal strain within the arc, but other major fractures bear no apparent relationship to plate tectonics. As to be expected, fracturing is more pronounced in the older carbonate units on all islands, but is obvious throughout the section. Undoubtedly many faults are still active. Fracture zones not only contribute to very high and anisotropic permeability, but also, when mineralized, may serve to increase hydrostatic heads by impounding groundwater, as has been recognized recently on Saipan.

Limestone formations older than the Holocene reefs have undergone a sequence of phreatic through vadose diagenesis. Mineralogy, stable isotope, and trace and minor element geochemistry indicate pervasive dissolution-cementation, replacement and neomorphism of original, unstable carbonate bioclasts and marine cements to calcite. Locally, diagenetic changes have been accompanied by extensive karstification, a condition seemingly related to water quality anomalies. Diagenetic changes have overwhelmed initial fabric-selective textures, exchanging inter- and intragranular porosity for cavernous, vuggy, channel, and occasionally moldic porosity.

Petrographic and structural geology studies of the aquifer limestone units are ongoing on Guam. Work is centered on describing the porosity-cement relationships from cores and cuttings and in better defining the fracture zones, especially their relationship to karst features, using remote sensing and field verification. Information is going into the GovGuam geographic information system to complement hydrogeologic data and results from proposed geophysical, drilling, and empirical mathematical modeling studies. A comparable level od research is needed on Saipan where well water is barely potable, and perhaps on Tinian and Rota as well.

## SHALLOW-WATER KUROKO-TYPE MINERALISATION IN FIJI

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Several small massive-sulphide deposits with Kuroko-type characteristics occur within acidic pumiceous rocks of the Late Miocene to Pliocene Udu Volcanic Group in NE Vanua Levu, Fiji. This sequence of acidic volcanic rocks covers some 750 $km^2$ and represents the youngest and most voluminous sequence of acidic volcanics in intra-oceanic arcs of the Western Pacific. In terms of volume, chemistry and to a lesser extent, volcaniclastic facies, the Udu volcanic sequence is closely comparable to the Miocene Green Tuff Belt of Japan.

Host rocks to the Fijian occurrences are high-temperature, high-Si rhyolites with reported Fe-Ti oxide equilibration temperatures between $900^oC$ and $1050^oC$. The rhyolites have an arc tholeiite chemistry with surprisingly low incompatible element abundances and flat REE patterns. Initial water contents of the rhyolitic magmas are estimated at <2-4 wt %.

Initial rhyolitic volcanism produced autoclastic flows and breccias with rare welded ash flows. Subsequent intrusion of rhyolitic domes was followed by highly explosive eruptions producing widespread pumiceous deposits. Relatively proximal pumiceous sequences show an abundance of large blocks, graded and cross-bedding, bioturbation and coral fragments, whereas relatively distal sequences contain doubly-graded pumiceous turbidites.

Kuroko-type mineralisation occurs in proximal situations in water depths estimated at less than 700 m. Much of the recent literature on Kuroko-type deposits has emphasised a deep water basinal location for the mineralisation albeit with conflicting arguments regarding the possibility of deepwater pyroclastic eruptions. We will stress that massive sulphide deposits, identical in many respects to Kuroko-type deposits can form in relatively shallow waters in an arc environment.

## OPERATION OF A SMALL OPEN–CYCLE OCEAN THERMAL ENERGY CONVERSION EXPERIMENTAL FACILITY

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There are two approaches to the extraction of thermal energy from the oceans, one referred to as closed-cycle and the other as open-cycle. In the closed-cycle surface (warm) seawater and deep (cold) seawater are used to vaporize and condense a working fluid, such as ammonia, which drives a turbine-generator in a closed loop, producing electricity. In the open-cycle, surface water is flash-evaporated in a vacuum chamber at pressures of ~2.6 % atmospheric. The resulting low-pressure steam is used to drive a turbine-generator. Cold seawater is used to condense the steam after it has passed through the turbine. The open-cycle can, therefore, be configured to produce fresh water as well as electricity.

Small OTEC demonstration facilities were operated for up to six months in Hawaii and Nauru, but unfortunately minimal operational data was obtained. These projects demonstrated that both cycles are technically feasible. Further analyses indicate that OTEC systems are only limited by the large diameters required for the cold water pipes, to sizes of no more than about 100 MW gross; and, in the case of the open-cycle, due to the low-pressure steam, the turbine is presently limited to sizes of no more than 3 MW gross.

As the next step, realizable with the minimal funding available, in the development of OTEC a land-based small experimental facility was designed and constructed by a team led by the author. The facility is presently operational at the Natural Energy Laboratory of Hawaii (NELH), Kailua-Kona, Hawaii. The power block was built around a single, vertical-axis, mixed–flow turbine, rated at 210 kW-gross, supported by a concrete vacuum vessel, 7.6 m in diameter and 9.5 m high. Steam is produced in an annular flash evaporator at the periphery of the vacuum vessel. The steam flows up from the evaporator and enters the turbine radially inward. The steam exists the turbine axially in the center of the vessel. A conical exhaust diffuser is used for pressure recovery. A direct-contact, structured-packing condenser composed of two coaxial stages is utilized.

The non-condensable gases liberated from the seawater streams, at pressures of 1.2 % to 2.6 % atmospheric, and a small amount of uncondensed steam is compressed and exhausted using a multi-stage vacuum compression system. All subsystems are instrumented to measure input and output temperatures and pressures as well as power output.

The data records obtained will be presented along with some of the questions related to the operation of OTEC plants and plans for the future.

## ASSESSMENT OF ENVIRONMENTAL IMPACT OF DEEP SEA MINING: ECOLOGIC STUDIES OF A MANGANESE NODULE FIELD IN THE PERU BASIN

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The vast resource potential of polymetallic nodules at the deep sea floor especially in the Clarion-Clipperton Zone of the Northeast Pacific Ocean will eventually stimulate industrial activities to extract the nodules comparatively high contents of manganese, nickel, copper, and cobalt, to use their catalytic properties in flue gas cleaning, and to use the residues as construction materials.

Deep sea mining of manganese nodules actually will have an environmental impact. However, we are far from being able to predict all possible consequences. It will probably take 20-30 years from now before full-scale deep-sea mining operation will commence. Thus, we have a good opportunity to gain a comprehensive understanding of the interaction of potential mining operations with the ecosystem and to assess the environmental risk well in advance of the actual beginning of operation.

In 1992, as a first step, BGR completed a study called "The Environmental Impact of Deep Sea Mining". The comprehensive report of more than 3000 pages covers various of nodule exploration, mining and smelting and their potential environmental impact.

As a second step, environmental field studies were conducted in a manganese nodule field of the Peru Basin. A long-term and large-scale sea floor disturbance and recolonization experiment was started in 1989 with RV *Sonne*. The seafloor and its fauna was studied mainly by biologists before and after disturbance. In 1992, again with RV *Sonne*, an interdisciplinary group of scientists worked in two undisturbed areas of the Peru Basin.

Using hydrosweep and parasound systems the bathymetry of the seafloor was mapped and the distribution of sediments was investigated. Deep towing of a side-scan sonar system revealed Mn encrustation of sediments and a nodule coverage of different density. Along the tracks of a photo sledge a great variability of bottom fauna and of bioturbation was observed. Apparently, nodules can be moved by benthic organisms which prevents them from been buried. The extreme size of nodules up to 21 cm in diameter, and the high abundance up to 43 $kg/m^2$ is explained by strong upward Mn flux due to mobilization within the reduced sediments of the last 2 Ma.

Bottom mechanical investigations of surface-near sediments completed on board. Large water samples were collected near the sea floor to determine character and amount of dissolved and suspended particles. Additionally pelagic organisms were gathered using large nets.

The results of this interdisciplinary study of an undisturbed area combined with the experience of a disturbed area will help to predict the environmental impact of deep sea mining and help to develop devices which have little disturbing influence.

# THEME: Seismicity and Volcanism: Natural Hazards and Tectonic Mapping Tools

## HAZARDS MAP OF THE CIRCUM-PACIFIC, SOUTHWEST QUADRANT

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Geological hazards in the southwest Pacific and southeast Asian region have caused billions of dollars worth of damage to property and agricultural lands, disruption of communities, and losses of human life measured in the tens of thousands. Yet how much information is available on these destructive events and how easily is it obtainable? Where and how often do these events takes place? Can the magnitude, intensity, and frequency of the events be recorded in such a form that they can be used to mitigate the effects of such hazards in the future? These questions underpin an effort begun recently in AGSO to map and assess the nature of geological hazards in the region. This effort is being undertaken against the backdrop of the 'IDNDR'.

1990-1999 has been designated by the United Nations as the *International Decade for Natural Disaster Reduction* (IDNDR). The objective of the Decade is to reduce, through intensive international action and especially in developing countries, the loss of life, property damage, and economic disruption caused by natural disasters. The goals are wide-ranging, but they include the devising of guidelines for applying existing scientific and technological knowledge to mitigate the effects of natural hazards. AGSO is participating in IDNDR activities through a natural-hazards mapping project. This includes the mapping of meteorological hazards as well as geological ones, and involves contributions from scientists from several other organisations, including especially the Australian Bureau of Meteorology, and also Macquarie University and the University of New England. The natural hazards mapping is coordinated through a Natural Hazards Map Working Group, consisting of 14 members, who meet annually at the Australian Counter Disaster College, Mount Macedon (Victoria).

Four different maps are planned for production during the Decade. The first of these is a 1:10 million map of natural hazards in the southeast Asian and southwest Pacific region, including Australia. It is to be published by the United States Geological Survey as part of the Southwest Quadrant series of geoscience maps produced by the Circum-Pacific Council for Energy and Mineral Resources through the Council's Circum-Pacific Map Project. An attempt is being made to represent the following three groups of hazard types on the map:

| | |
|---|---|
| Group 1 | Earthquakes, volcanoes, tsunamis, cyclones and landslides |
| Group 2 | Severe storms, droughts, floods and bushfires |
| Group 3 | Wave heights, pack ice and icebergs, and superstructur ice |

Group 1 hazards are those able to be represented most easily throughout the region on the basis of existing data. Group 2 hazards can be represented on the map for Australia, but less well (if at all) for the remainder of the region because of difficulties in accessing any existing data. Group 3 hazards are of lesser importance, but are easily represented on the map because they occupy the Antarctic parts and therefore there will be minimal overlap with hazards represented in the central and northern parts of the map.

A second map being considered by the Natural Hazards Map Working Group is a 1:5 million natural-hazards map of Australia. Two other possible maps are being considered for later in the Decade, but these depend heavily on data availability. They are (1) a 1:10 million-scale natural-hazards risk map of the Southwest Quadrant, and (2) a multi-hazard potential map of the Southwest Quadrant in which the difficult problem of ranking and combining different natural hazard types would be tackled (the idea would be to represent the 'hazardousness' of different areas by a single parameter, or factor, and then to contour the entire region).

The availability of data on several important natural hazards is a serious problem for the southwest Pacific and southeast Asian region. There are digitally based data available for hazards such as earthquakes and cyclones, but information on other hazard types is dispersed widely, non-digitally, and obscurely in some areas. These limitations affect the ability to assess the past impact of different hazard types in the Australian region. There is a clear need to attempt to collect or network data digitally using a Geographic Information System (GIS) for hazard data throughout the southeast Asian and southwest Pacific region. AGSO and the Bureau of Meteorology recently made a commitment to explore jointly the possibility of establishing a national GIS network for natural hazards that could serve as a resource for emergency services, land-use planners, the insurance industry, and other groups concerned with the impact of natural hazards. A regional natural-hazards GIS network would represent a major outcome for the IDNDR in the region.

## SEISMICITY AND SEISMIC RISK OF FIJI


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The seismicity of Fiji is concentrated along major known tectonic features, however it is not limited to these areas as earthquakes have occured almost everywhere in Fiji, although at a lower level. The seismic zones of concern, in terms of risk, are those close to populated areas.

The highest seismic energy release area is in the **Udu-Taveuni** area where two distinct pockets of activity can be observed. One pocket lies close to eastern Vanua Levu and Taveuni (16.5°S and 180°) and the other about 80 km east-northeast of Udu Point (16.0°S and 179.5°W). The area of activity close to eastern Vanua Levu and Taveuni is the source area for the earthquake, magnitude $M_S$ 6.9 in 1979 which caused landslides and damage to buildings in Taveuni. Four more earthquakes with magnitude at least 6.0 have occured here in this century. The second pocket of activity in this area has had several large earthquakes this century, however, major damage is not expected from earthquakes here.

Most frequent occurrence of earthquakes is in the zone **northeast and northwest of Yasawas**. Most of the activity in this zone occur in the trough areas, Yasawa Trough and Yadua Trough. The areas that are likely to get affected by large earthquakes in this zone are western Vanua Levu and Ysaswas. Although strong shaking can be experienced in the Yasawas, little damage is expected because of mostly traditional types of dwellings.

Moderately high level of seismic activity exists **southwest of Kadavu**. Small earthquakes in this area are not as frequent as the areas mentioned above. Swarms of small earthquakes have occurred near Kadavu in 1981 and 1983. During the 1983 swarm three earthquakes of magnitude about 5 occurred. These caused some landslides in the south-western part of Kadavu. Large earthquakes have occurred in 1935 and 1950.

Low level of **scattered seismicity** occur in various areas of Fiji. Areas where these are more common are near the Island of Ovalau, southern Viti Levu and west of Viti Levu. Small earthquakes have occurred in central Viti Levu, southern Vanua Levu, northest of Viti Levu and near Matuku. An earthquake of magnitude 4.8 also occurred close to Lakeba, an area previously considered to be aseismic. Large earthquakes have occurred near Suva, near Koro Island and south of Taveuni. The earthquake near Suva ($M_S$ = 6.8) occurred in 1953 and caused reef cracks, extensive damage to Suva sea wall and produced cracks in many buildings. The earthquake also generated a devastating tsunami. Eight people died as a result of injuries received and drowning.

The level of seismic activity near Suva is low, but it is without doubt the most vulnerable area with regard to earthquake risk. A similar earthquake to that of 1953 would probably result into many fatalities and many million dollars worth of damage.

The areas of low level of microseismicity do not readily lend themselves to an assessment of seismic risk. Calculation of earthquake return periods is also very difficult as the recorded history of Fiji is very short.

## SEISMOTECTONICS OF THE HORN RIDGE (FUTUNA AND ALOFI ISLANDS), A ZONE OF CONVERGENCE IN THE FIJI FRACTURE ZONE

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The March 12, 1993 Futuna earthquake (14.248° S, 178.298° W, focal depth "normal", Mb=5.9, Ms=6.5 PDE) killed three people and caused spectacular damage to structures all over the island. It produced numerous landslides onshore all around the island, and offshore triggered a small tsunami. It also very likely uplifted part of the island at least 50 cm as is shown by the newly uplifted coral reefs of the southern coast. This quake was strongly felt with an intensity 8 on Mercalli scale all over the island. Such a high felt intensity is uncommon and has not been reported since May 1840, when a similar quake shook the island (Saint Pierre Chanel, 1840). The collapse of most of the historic buildings (from the beginning of the colonization) during the March 12 event also supports the idea of an unprecedented earthquake since the May 1840 event.

The Horn islands (Futuna and Alofi) are located very near the North Fiji fracture zone which limits to the north the Lau basin and the Fiji platform. The seismicity of the area surrounding Futuna and Alofi islands falls in two groups: the seisms from the Fiji fracture zone, at a minimum distance of 50 km, and the nearby events located on the southern edge or underneath the Horn platform. The Fiji fracture earthquakes are usually felt as short tremors and probably never caused important damage on Futuna by shaking only (there is a significant risk of tsunami from regional earthquake). The local events are strongly felt and can cause damage according to the magnitude. These two zones of seismicity are characterized by different focal mechanism type. The Fiji fracture zone mechanisms are strike slip solutions with an E-W oriented subvertical fault plane while the two published mechanisms near Futuna (3/27/86 and 3/12/93 events) are thrust solutions with, in both cases, a fault plane oriented N300. This direction is subparallel to the strike of the southern flank of the Horn platform. The two thrust mechanisms are interpreted to indicate the slip motion of the oceanic crust of the Lau basin beneath the Horn platform. However the SW-NE P axis orientation of the focal solutions are identical in both zones and indicate an homogeneous regional stress field.

A three component digital seismic station was deployed two days after the March 93 event. The rate of aftershocks reached one event per minute in the early days after the main shock. Forty large aftershocks have been located and allow definition of the geometry of the fault plane ruptured during the March 93 seismic sequence. The S-P relative travel time of the aftershocks spread from 0.7 to 3.4 seconds with 66% of the data between 0.7 and 1.7 seconds. The location uses the observed back azimuth and incident angles measured on the three component seismogram. The epicenter and the depth are then computed by ray tracing back to the source using the travel time difference between P and S waves. The velocity model used for the location is a simple half space with velocities appropriate for basalt. The error on the location is about 2 km. The aftershocks cluster near the seismic station with most of them spread beneath the central part of the Futuna island while the main shock has been located 15 km westward offshore by USGS.

The size of aftershocks zone is compatible with the surface rupture of a magnitude 6.5 event and strongly suggest that the fault plane of the March 12, 1993 earthquake is indeed located beneath the Horn platform. The nearness of the fault is also supported by the numerous sonic waves heard by the island population during the seismic sequence. The focus depth spread between 7 and 20 km. The maximum depth indicate the Horn ridge has a thick crust probably of island arc type. The seismicity pattern suggest the island is bounded by two major faults, one along the northeastern coast with a subvertical dip, the other striking N300 along the southwestern coast and dipping under Futuna with a steep angle in agreement with the dip angle given by the focal mechanism solution of the March, 1993 earthquake. The dip difference between the March 1986 (30°) and the March 93 (60°) events indicate that they have ruptured two different segments within the same fault system striking N300.

The Horn ridge is characterized by a crustal seismicity spreading down to 20 km. The induced crustal deformation leads to the surrection of Futuna and Alofi islands and are controlled by a shortening process evidenced by the inverse faulting mechanisms of the major earthquakes located close to the ridge. This zone of shortening is interpreted as related to an irregularity of the plate boundary between the Pacific plate and the plates of the Fijian platform and of the Lau basin. This plate boundary is a left lateral transform fault segmented by zones of spreading or convergence.

The seismicity pattern and the focal mechanisms clearly show that this plate boundary is wide (about one degree at 176° W) and that the deformation within this strip is complex. The easternmost east-west oriented segment runs from the northern end of the Tonga trench to the southeast of the Horn ridge. Afterwards, the northern limit of this plate boundary would follow the southern flank of the Horn ridge, striking N300, creating a zone of compression. Another segment of the Fiji fracture zone runs between 179° W and 178° E. It is shifted southward with respect to the eastern segment of the fracture zone and to the Horn convergence zone. This configuration implies the presence of a N10E oriented spreading zone around 178.5° W in order to connect the two shifted segments of the Pacific plate boundary.

## RETURN PERIODS OF LARGE EARTHQUAKES IN PAPUA NEW GUINEA

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An investigation of earthquake hazard in Papua New Guinea (PNG) by a yearly extreme magnitude method utilizing the magnitude 7 earthquake record since 1900 shows that the Bougainville Island seismic zone is by far the most active, followed by the New Britain and northern mainland PNG regions.

The method used was the Type 1 Gumbel extreme magnitude analysis which has been described by Epstein and Lomnitz (1966) and Lomnitz (1974). Lomnitz applied the method to the seismicity of California. Following Lomnitz, the Type 1 Gumbel distribution is given by

$$G(M) = \exp(-\alpha e^{-\beta M}) \qquad (1)$$

where G(M) is the probability that earthquake magnitude M will not be exceeded in any given year, $\alpha$ and $\beta$ are constants, $\alpha$ being the mean number of earthquakes per year above magnitude zero.

The Type 1 Gumbel distribution can be rewritten

$$-\ln(-\ln(G(M))) = \beta M - \ln\alpha \quad (2)$$

To estimate the parameters $\alpha$ and $\beta$, the largest yearly earthquake magnitudes in a sample of n consecutive years are selected. These magnitudes are arranged in order of increasing size, so that

$$M(1) \leq M(2) \leq M(3) \ldots\ldots \leq M(n) \quad (3)$$

$$\text{Then } G(M(j)) = j/n+1 \quad j = 1 \ldots\ldots n \quad (4)$$

The values of $\alpha$ and $\beta$ are then obtained from the least squares fit to the probability relationship

$$-\ln(-\ln(G(M))) = \beta M - \ln\alpha \quad (2)$$

In addition, the number of earthquakes in a given year with magnitude exceeding M is

$$N_M = \alpha e^{-\beta M} \quad (5)$$

$$\text{Hence } \ln N_M = \ln\alpha - \beta M \quad (6)$$

$$\text{and } \ln T_M = \beta M - \ln\alpha \quad (7)$$

where $T_M$ is the return period of an earthquake of magnitude M.

For PNG seismic regions, two sets of data are combined to give the single probability relationship. The set of magnitude 7 earthquakes which have occurred over the 91 year period 1900 to 1990 is combined with the set of earthquakes which have occurred in the 27 year period 1964 to 1990.

Relative seismic activity levels or return periods between the zones cannot be compared directly because the zones differ in area. Hence a second relationship has been derived for each zone, normalized to an area of 10,000 $km^2$ (a 100 km square, or a circle of radius 56.4 km). Return periods derived from the normalized relationships then refer to any 100 km square or 56.4 km radius circle within the zone, centred, for example, on any project or development site within the zone.

Return periods are compared with those for the State of California in the USA and California Seismic Zone 4, determined by the same method. The whole of the State of California is considered to have a high earthquake risk. The State comes under USA Seismic Zone 3, where earthquake damage can be expected at the level Intensity 7, except for the part of the state in Zone 4, which is Zone 3 but close to major fault systems. Since 1900, California has experienced nine magnitude 7 earthquakes, including the "great" San Francisco earthquake of 1906. Seven occurred in Zone 4 and two in Zone 3. Normalized to the 10,000 $km^2$ area, return periods of a magnitude 7 earthquake in California State and California Zone 4 are approximately 600 and 300 years respectively.

Since 1900, PNG has experienced over 100 magnitude 7 earthquakes. While many of these caused damage, or would cause damage if they occurred today, many are either deep or beneath the Solomon and Bismarck Seas, where the main threat is from tsunamis.

A region with a similar level of seismic activity to California is the Papuan Fold Belt. The Belt extends from Kerema on the Gulf of Papua in the southeast through Lake Kutubu and Star Mountains across the border into Irian Jaya. The seismic zone is not merely the southern margin of mainland New Guinea seismicity, but is a separate shallow earthquake zone.

The Fold Belt contains major mineral and petroleum developments. The Ok Tedi mine in the Star Mountains is a major producer of gold and copper. Oil is piped from the oil field at Lake Kutubu to Kikori on the coast and on to a tanker mooring for export.

Magnitude 7 earthquakes have occurred on the Papuan Fold Belt in 1922 south of Lake Kutubu, in 1954 near Tari northwest of Lake Kutubu, and two in 1976 just over the border in the Irian Jaya Star Mountains in which over 500 people were killed. Earthquake magnitude 7 return period for a 10,000 $km^2$ normalized area is approximately 400 years (cf. California State and Zone 4,600 and 300 years respectively).

The most active part of PNG is the Bougainville Island region. A Wadati-Benioff earthquake zone dips from the Solomon Sea northeast beneath Bougainville, associated with the subduction of the Solomon Plate in front of the advancing Pacific Plate. Two magnitude 8.0

earthquakes occurred in 1971 in the northern Solomon Sea and caused tsunamis along the Bougainville Island coastline and other northern Solomon Sea coastlines. The 10,000 $km^2$ normalized earthquake magnitude 7 return period for the zone is approximately 40 years (cf. California State and Zone 4, 600 and 300 years respectively).

The northern Solomon Sea island of New Britain has a normalized earthquake magnitude 7 return period of 60 years. The seismic zone is associated with the subduction of the Solomon Plate beneath New Britain as the island advances over it. Magnitude 7 earthquakes include a shallow central New Britain shock in 1985 which caused damage on both northern and southern coasts. Massive landslides in the central mountains dammed the Biaraman River and the dam had to be removed by blasting.

The Huon Peninsula region north of the city of Lae lies over or close to the triple-junction of the India-Australia, South Bismarck and Solomon Plates. The Solomon Plate forms an arch beneath the region and is slowly sinking, with Wadati-Benioff zones dipping both to the north and south. A recent magnitude 7 earthquake, in 1987, killed three people on the Huon Peninsula and caused considerable damage on nearby Umboi Island. The normalized 10,000 $km^2$ magnitude 7 return period is approximately 80 years (cf. California State and Zone 4, 600 and 300 years respectively).

Northern mainland PNG experiences large earthquakes at both shallow and intermediate depths. The shallow earthquakes are associated with the collision of the South Bismarck and India-Australia Plates, and the intermediate depth earthquakes with the sinking Solomon Plate beneath the collision zone. A damaging magnitude 7 earthquake occurred at Wewak in 1968. A magnitude 7.9 earthquake occurred beneath the Torricelli Mountains of the northern coastal region in 1935, during which objects were thrown into the air, suggesting to the observer that accelerations exceeding "g" had occurred. The normalized 10,000 $km^2$ magnitude 7 return period is approximately 120 years.

Of other regions, the normalized return period for the islands of the Bismarck Sea and Pacific Ocean is approximately 640 years. Two magnitude 7 earthquakes occurred about 70 km north of Lihir Island in 1944, for example. The value for the Papuan Peninsula is approximately 470 years, although no magnitude 7 earthquake has occurred in the Peninsula since 1900, and the largest recorded earthquake was of magnitude 6.2. It occurred in 1979 and caused damage in the capital city of Port Moresby.

References

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Lomnitz,C., 1974. GLOBAL TECTONICS AND EARTHQUAKE RISK. Elsevier, Amsterdam.

# THEME: Mapping Coastal Zone Geology for Development and Climate Change Vulnerability

## LITTORAL EROSION OF THE CORAL ISLAND OF AMEDEE LIGHTHOUSE, NEW CALEDONIA, SOUTHWEST PACIFIC

*M. Allenbach*

French University of Pacific, BP 4477, Nouméa, NEW CALEDONIA

Summary: *The coral island of Amedee Lighthouse, situated offshore from Noumea (New Caledonia), is subjected to littoral erosion which threatens the beaches, the natural stabilized soil and the infrastructures of the island. The analysis of the generating mechanisms, the definition of the characteristics of the littoral sedimentary dynamics and the qualification of volumes in action denote the reality of an actual significant retreat of the coast.*

About 10 miles from the coast of the mainland, in front of Noumea, the island of the Amedee Lighthouse (long. 166°27'88E, lat. 22°29'17S) is situated close by the Boulari Pass which allows the access to the New Caledonia Lagoon. As the top level tourist resort of New Caledonia and famous for its lighthouse of 56 meters high, the island is shown under the form of sandy reef roughly rectangular and oriented to South West-North East. It concerns of an accumulation of bioclastic sand of about 300 meters long and over 150 meters wide, fixed by the natural vegetation in its central part. The soil and the beaches surrounding the island are resting on a hardened coral substratum of beach-rock type visible at the South West peak and on the coral reef flat which runs the emerged part of the site.

Till the outer falling which assures the connecting with more important depths of the lagoon, the coral reef flat easily to be seen at low tide presents a very regular morphology on the essential part of the circumference of the island. The bottoms are almost flat, not very deep. Only the Northern facade escapes to this general scheme and shows two little passes which are perpendicular to the outline of the coast, cutting up into the coral reef flat. The latter has more imposing dimensions than those of the emerged part of the island. It has a roughly lozenge shape, the big diagonal of which would be orientated East- Westwards for a length of about one km and the small diagonal orientated North-Southwards for a length of about 700 meters.

Warned by the traces of a recent erosion affecting the North East-South West littoral of the island, the Sea Services of the South Province of New Caledonia has asked for the carrying out of a survey aiming at defining the generating mechanisms of erosion and quantifying its dynamics. The survey is actually in its final stage of achievement. It was stated into three stages:

- a comparative analysis of the cartographic and photographic documents of the site, coupled with an inquiry making after people frequenting regularly the island;
- a survey at the "initial adjustment" of the site consisting of a detailed topographic survey, the achievement of 9 profiles of outlier resorts and of a range of sedimentological samplings of the aerial and submerged shores. This survey has been completed by a bibliographical analysis of the meteo-oceanological environment;
- a follow-up of the site on an annual cycle with the carrying out of topographical surveys and quarterly repetitve profiles of beach joined with a currentological survey by letting go the drifting floats.

The principal results actually acquired bear on the following points:

- *sedimentological cartography of the sub-marine bottoms of the littoral coral reef flat and of the aerial beaches of the island.* Four great areas have been noticed and mapped at the level of the coral reef flat on basis of a ratio of coral recoverings in place/beaches of sand. The samplings of the light sediments carried out on the subaerial and submerged beaches prove a rather coarse bioclastic sedimentation amongst which two granulometric stages sharply specified and unequally spread over the circumference of the island have been recognized: clear majority of bioclastic sands (85% of samples) at the level of the subaerial beaches and of the little bottoms near of the outline of the coast and gravels and biogen shingles at the level of the outer detritical collecting and in the Northern beach area of the island. The small fraction, less than 63 micrometers, is negligible on the whole area (< 1%). The sedimentological repartition of the surface put into evidence is directly liable to the ambient hydrodynamism;

- *definition of the of the sedimentary dynamics.* The erosion which attacks the North-Eastern littoral of the island of Amedee Lighthouse is a phenomenom relatively recent which was set off in 1988 after the passage of a cyclonic depression on the South region of New Caledonia. A natural part of barrier reef of sands and bioclastic gravels roughly orientated South Northwards and based on discontinuous outcrops of beach-rock was caused to become fragile by the paroxysmal hydrodynamism involved in the passage of the cyclone. A part of the light material, but fixed, of the barrier reef is found remobilized and integrated in the littoral drifting movements. Since then, the conditions of an erosion of the Northern part of the island are found combined with the creation of a channelisation parallel to the littoral. Considerating the general orientation of the coast (SW-NE), of the prevailing hydrodynamism (dominating regimes of West and SouthEastward) and of the shape of the island at its septentrional peak, a new sedimentary dynamic was put into place with the search for a natural new balance. There was erosion of the North-West part of the island and accretion of the South-West and North-East areas by sedimentary transits;

- *quantification of sedimentary movements.* The topographical surveys shows a retreat of sandy spur and of the northern beach at the scale of 2000 $m^2$ between October 1990 and May 1992 with a linear retreat of 50 m on the profile transversal to the coast, creation of a live microcliff at the top of shore warning the erosion of the stabilized soil of the island, erosion especially sensible by sea at West regime and high coefficient of tide. The top of shore is moreover destabilized by the abthropic activity due to the passage of full quotas of visitors on the island (25000/year). The repetitive surveys carried out subsequently to the null point of the site show that till this day (June 1993), the dependent dynamic is not reduced. The linear retreat of the stabilized old soil of the island up-side of the microcliff was reckoned at 3 m for the last six months on the most threatened segments of the coast.

## HOLOCENE EVOLUTION OF THE REWA DELTA, FIJI

*Jared Armstrong and Graham Shorten*

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The southeastern corner of Viti Levu in the Fiji Islands is impacted by south easterly winds all year around. It is in this wave and wind dominated environment that the Rewa River empties into the sea. The river experiences annual flooding during the monsoon times which causes varying degrees of damage to villages and other infrastructure along the river banks of the lower delta. Dredging is the only method employed to counteract this flooding effect in the lower river delta area, and has not been that successful.

A small coastal geological study has been undertaken with a view to try and understand the interplay of coastal processes responsible for erosion and deposition at various locations along the river. The different sub-aerial and subaqueous sedimentary units deposited during this time are interpreted to understand the environment during the Holocene epoch when the delta was formed. It is hoped that the data will help develop informed flood mitigation strategies for the river.

A seismic and bathymetric survey were undertaken, air photo interpretations were done and samples were collected for grainsize analysis, calculations of Atterberg limits and Carbon 14 dating.

The bathymetric results show a ramp in the river near the top of Selo island. Seismic results show a change in the geology of the area at the river mouth. Both the bathymetric and seismic results imply that a Pliocene-Pleistocene reef system may exist beneath the delta similar in morphology to Nukubuco Reef in Laucala Bay. This reef was slowly inundated with river sediment at the close of the last Holocene stillstand. The Rewa delta is interpreted to have existed since this time and a model for the delta progradation during the Holocene is proposed.

Grainsize distribution and Atterberg limits from the different morpho-stratigraphic units are used to construct an environmental engineering map of the area. Based on the information gathered, recommendations for flood mitigation strategies and further work in the area are given.

## DEVELOPING STANDARDS FOR MEASURING COASTAL CHANGES IN THE SOUTH PACIFIC REGION TO ASSESS VULNERABILITY TO CLIMATE CHANGE

*Rick Gillie*

Axys Environmental Consulting Ltd P O Box 2219, Sidney V8L 3S8, B.C., CANADA

Future possible accelerated sea-level rise and changes in the pattern, frequency and intensity of cyclones which may be associated with global climate change is a recognised concern in Pacific Island countries, especially those with significant areas of low elevation shorelines such as atoll and table reef islands and deltas. Two questions need to be addressed in order to assess the likely vulnerability of these shorelines to climate changes. First, how have these shorelines responded to changes in the past, secondly, how will the shorelines respond in the future? This paper provides a means of answering the first question and proposes the development of standards for measuring shoreline changes in the South Pacific region.

Shoreline erosion and its impact on man's use of the coastal zone is presently a serious problem in many parts of the South Pacific region. Despite this, there are few well documented studies of shoreline changes based on data collected over a significant period of time (usually 20–50 years). Shoreline change problems should be addressed on the basis of reliable information about rates of coastal retreat (and, where accretion is taking place, rates obtained there should be dependable). Unfortunately, various constraints on the ability to derive the necessary data, such as scale limitations, map standards, lack of control and the means of measurement (precision and accuracy) may render so-called measurements meaningless. Many of these constraints are treated in this paper.

Rates of long-term (50 years) shoreline change have already been based on measurements from aerial photographs, historic charts and maps. On the other hand, beach profiles have been used primarily to measure shoreline changes within shorter periods (1-10 years). For determining rates of change, surveying and profiling are generally considered to be the most precise and accurate methods. Profiles are also useful for delineating the relationship between water levels and the predicted and surveyed positions of mean sea level, mean high water, etc. Measurements of long–term coastal changes are most accurately done using a combination of aerial and profiling surveys.

Determination of the water/land interface from aerial photos along a mangrove coast must be approached quite differently than on an open, sandy or gravel shoreline. The principal difficulty in identifying the shoreline changes is that the water/land contact is concealed by the vegetation canopy and thus not visible. However, there may be a possibility that a measure of the shoreline change can be determined if the position of the leading edge of the mangrove forest can be compared from two photos.

Beyond the questions of accuracy of various monitoring methods and the inherent problems of scale and human measurement error, are broader questions dealing with temporal variability of shoreline changes and the reliability of calculated rates of change. Shoreline changes occur in response to a hierarchy of natural cyclic phenomena including tides, seasonal changes in wave climate, storms and cyclones and sea level changes and longer term El Nino cycles. Short term catastrophic erosion of the shoreline may give erroneous data since, within several months to a year, the shoreline may adjust to its former position. Potential problems of short term temporal variability can be minimized by properly desinged beach profiling programs and an increased awareness of the complete range of coastal change processes.

## APPLICATION OF THE IPCC COMMON METHODOLOGY FOR ASSESSING COASTAL VULNERABILITY TO SEA-LEVEL RISE IN SOUTH PACIFIC NATIONS UNDER THE US SUPPORT FOR COUNTRY STUDIES

*Rick Gillie*

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In 1992, the United States announced an initiative to provide funds to help countries prepare studies to address climate change. Among other things, these studies would enable countries to assess their vulnerabilities to climate change and evaluate response strategies for mitigating and adapting to climate change. Included within the scope of work are assessments of coastal vulnerability to accelerated sea level rise (ASLR). To be eligible for funding under the Country Studies Program countries must have signed the Framework Convention on Climate Change or stated their intention to do so (U.S. Government, 1992).

The suggested methodology for use in coastal studies will come from the Coastal Zone Management Subgroup of the Intergovernmental Panel on Climate Change (IPCC) - Working Group III Response Strategies. The methodology is known as "A Common Methodology for Assessing Vulnerability to Sea Level Rise" (IPCC, 1992). The Common Methodology comprises a stepwise approach for the actual execution of the coastal vulnerability analyses case studies, as outlined below.

In order to complete the assessment, geologic conditions and terrestrial/nearshore marine processes need to be understood in order to evaluate hazards associated with the coastal environmental and ASLR and the potential impact of response strategies by man on coastal systems. Therefore, it is clear that geoscience organisations in the South Pacific, such as SOPAC and national bodies, have an important role to play in this process. In this regard, a 1992 report by ESCAP has noted that geoscientific data are becoming increasingly important for the assessment and management of complex coastal systems. Geoscientists in the Pacific have already demonstrated a capability to address coastal zone management and development needs.

Further examination of the seven steps in the Common Methodology reveals the role of the geosciences in the assessment, particularly in steps 1, 2, 4, 5 and 7:

1. *Delineation of case study area.*

The case study area is defined as the area for which a vulnerability profile is to be determined. The study area may be a specific island or region within a country or an entire country. The inland extension of study areas should encompass the areas which are physically affected by ASLR through changes in the probability of flooding, in erosion and sedimentation patterns or in salinity intrusion. The case studies will use two distinct sets of boundary conditions for ASLR to be reached in the year 2100: 0.3 metres which represents a low estimate and 1.0 metres which is based on high estimates.

2. *Inventory of study area characteristics.*

This step is involved with the collection of all relevant study area data, which includes but is not limited to physical characteristics (coastal types, sediment transport, location, nature and extent of coastal erosion and protection facilities, etc).

3. *Identification of relevant development factors.*

Within the concept of vulnerability, the nature and extent of human activities play a critical role. The most relevant development factors are considered, from the point of view of possible consequences, rather than actual economic development projections.

4. *Assessment of physical changes and natural system responses.*

The major potential physical changes imposed by ASLR include; (i) morphological development of the shoreline and floodplain (erosion/accretion), (ii) water levels of coastal and tidal areas and (iii) salinity changes of surface and groundwater bodies. These physical changes may result in three different types of natural system response: direct loss, increased risk and other damages.

5. *Formulation of response strategies and assessment of their costs and effects.*

The possiblities and effects of response options (within the main categories: retreat, accommodate and protect) are an integral part of the assessment. At least two extreme cases are considered: a situation with no action and a full protection response.

6. *Assessing the vulnerability profile and interpretation of results.*

This is a complex and sometimes difficult step, the success of which depends on the ability to define the conditions in previous steps and apply cost/benefit analysis.

7. *Identification of the needs and plans of action.*

The plan of action should provide the country's decision makers with appropriate conclusions, recommendaions and proposals in order to given an outline for immediate, medium and long term action in the framework of a nation's coastal zone management programme.

References

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ESCAP, (1992), Study on benefits to be obtained from rational coastal resource management: geoscientific applications. Economic and Social Commission for Asia and the Pacific, United Nations, New York. 87 pp.

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## STATUS OF NASA AIRCRAFT RADAR MEASUREMENTS OF THE SOUTH PACIFIC REGION

*Donald R. Montgomery*

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(no abstract received)

## COASTAL EROSION INVESTIGATIONS AT YANUCA ISLAND AND CUVU HARBOUR, FIJI

*Satish Prasad*

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The north-west coast of Yanuca island is being seriously affected by coastal erosion. The erosion problem has been exacerbated by human activities such as mining of sand from the spit and beach, clearing of coastal vegetation, construction of vertical sea walls, and lack of understanding of the dynamic nature of the coastal environment.

Prior to development of The Fijian the beaches were stable with no evidence of erosion. Since development, this stability has been adversely affected such that coastal erosion is now considered a serious problem with beach areas being lost and recreational structures affected.

Examination of historical aerial photographs and maps, and discussions with local elders, revealed that the coastline around Cuvu Harbour, especially Yanuca island's north-west coast, is highly dynamic and sensitive to both human activities and cyclonic events. Long-term cyclic changes in the position of the channel opening could occur under natural conditions.

Short-term monitoring of the beach profiles around Cuvu Harbour indicates that most profiles are generally similar and show very few marked changes. Of the ten profiles monitored (excluding profiles 6, 7, and 8 due to human interference), eight showed nett accretion and two showed nett erosion. One profile showed a continuous accretionary trend, another showed a continuous erosional trend, and eight showed cycles of erosion and accretion.

It is recommended that the sand extraction and clearing of vegetation from the sand spit and construction of engineering structures in the dynamic coastal zone should be prohibited. The vertical timber wall should be removed from the eroding coastline and an artificial beach nourishment programme should be undertaken.

## VOLUMETRIC MODEL OF THE MONASAVU LAKE, VITI LEVU, FIJI

*Robert Smith*

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The Monasavu dam located in northern central Viti Levu is one of Fiji's important public assets. The performance of this reservoir, particularly in periods of law rainfall, has a direct bearing on the supply electricity to the main population and business centres of Fiji. To determine an accurate reservoir height-volume relationship for Monasavu Lake for energy planning the Fiji Department of Energy requested SOPAC to obtain a detailed hydrogeological model of the reservoir.

Acquisition of data for compiling this model was carried out between the 16 and 21 of March 1993 at which time the Lake was filled to full capacity. For the survey navigation control was by the microwave trisponder system and depth was recorded by a Raytheon DE791e echo-sounder. Data was logged digitally. It is estimated that 63% of the lake was surveyed based on current figures available for the surface area of the Lake at full supply level.

The model determined from this work is based on some **6787** data points which have been compiled from the survey data known bench marks and data digitized from 1:5000 reservoir contour maps. Preliminary results from the model appear to reflect good correlation with the current formula used to calculate the available service volume.

## AGGREGATE INVESTIGATIONS ON SMALL TROPICAL LIMESTONE ISLANDS

*D.R. Tappin*

British Geological Survey, Nottingham, England

On small tropical limestone islands there are few indigenous sources of building and civil engineering materials: aggregate resources are in short supply. In 1990 a project was formulated to address the problems of aggregates supply using the Kingdom of Tonga as a model. The project was part of a Research and Development programme funded by the Overseas Development Administration of Great Britain and administered by the British Geological Survey. There were two aspects: limestone aggregate evaluation and the assessment of beach-sand supply. The limestone resource survey included testing for the physical, mechanical and chemical properties of the limestone aggregate and included guidance in minerals planning. However, this talk deals only with those aspects of the project concerning the beach-sand assessment.

The beaches of Tonga are the only source of sand except for quarry fines. Extraction of sand from the beaches of Tonga has long been a cause of concern because of the environmental damage, but in the absence of an alternative sand source beach-sand extraction has continued to take place. The beaches are the first line of defence against erosion by the sea, they are also a recreational facility. No quantitive estimate has ever been put on the beach-sand reserves, nor on the effects of extraction. The aims of the project therefore were to quantify the beach-sand resource and the rate of erosion; assess the impact of sand extraction; and to identify those beaches from which sand could be extracted with the minimum of environmental damage.

A further aspect of the project was to put the beach-sand resource into context with the newly discovered sand resource offshore of Tongatapu. This sand source was identified by SOPAC in 1991 and offers a potential sand supply that represents over 200 years of reserves at the present rate of demand. Additionally the project was to establish a methodology whereby beach-sand resources could be rapidly assessed.

The beach-sand is almost entirely carbonate derived from the fringing-reef. To estimate the beach-sand resources most of the main beaches on the larger, most developed, islands were surveyed. Over 200 beach profiles were acquired at an average spacing of 75 metres. To rapidly acquire accurate survey data an electronic level, a Total Station, was used. Distance and height measurements are recorded as horizontal and vertical angles and a slope distance and are stored on a micro-computer that also converted the data into x,y,z coordinates. Sediment depth measurements were taken with a 3 metre long steel rod.

The beach-survey data was downloaded from the micro-computer onto an 'AUTOCAD' computer-aided draughting system. The two-dimensional depth profiles were hand-drawn and digitised. Beach-sand areas of each profile were calculated and sand volumes estimated by the input of the horizontal survey data. Tonnages were calculated from beach-sand densities measured at BGS laboratories. To estimate the likely sediment contribution from the reef, three values had to be calculated/estimated; the area of the reef adjacent to the beaches, the production of calcium carbonate from this reef area, and the volume of this sediment that was likely to be cast up onto the beach. To monitor temporal changes in beach widths, aerial photographs from 1968, 1980 and 1990 were interpreted. a period of 22 years.

The results of the survey show that over the past 25 years the beaches from which sand had been extracted have diminished in size, with some beach widths halved by up to 50%. For Tongatapu, overall natural beach-sand replenishment rates from the reef are 50% of the present annual rate of extraction. However, on those beaches preferentially used for sand extraction the replenishment rate may be as low as 16% of the annual extraction rate. An extraction strategy has been devised, but total sand reserves are finite and continued extraction will lead to further environmental damage to the beaches.

## STAR PROGRAM AND ORAL PRESENTATIONS

### *Saturday 2 October*

| | | |
|---|---|---|
| 19:30-20:00 | Welcoming Address by Chairman of STAR | Keith A.W. Crook |
| 20:00-20:30 | Pacific Plate Motions, 0-150 Ma, in the Hotspot Frame of Reference | L.W. Kroenke and C.Y. Yan |
| 20:30-21:00 | Evolution of the Lau Basin: Implications for the Geology of Arc-Backarc Systems of the SOPAC Region | James W. Hawkins |
| 21:00-21:30 | Early Tertiary Rocks in Fiji | Howard Colley |
| 21:30-22:30 | Working Groups | |

### *Sunday 3 October*

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|---|---|---|
| 19:30-22:00 | Working Groups | |

### *Monday 4 October*

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|---|---|---|
| 13:30-14:00 | Magnitude and Timing of New Hebrides Arc Rotation Following Spreading Propagation in the North Fiji Basin: Palaeomagnetic Evidence from Nendo, Solomon Islands | Robert J. Musgrave and John V. Firth |
| 14:00-14:20 | Cenozoic Compressional Tectonics on the Fairway Ridge and the Lord Howe Rise between New Caledonia and Australia | Yves Lafoy, B. Pelletier and J.-M. Auzende |
| 14:20-14:40 | New Constraints on the Permian to Eocene Tectonics of the SW Pacific: Evidence from New Caledonia | Sébastien Meffre, J.C. Aitchison and D. Cluzel |
| 14:40-15:00 | Preliminary Estimates of Sedimentation Rates in Modern Convergent Margin-Related Basins in Papua New Guinea | Keith A.W. Crook, Benny Kruman and Gregory Whitmore |
| **15:00-15:30** | **AFTERNOON TEA** | |
| 15:30-16:00 | Seismotectonics of the Horn Ridge (Futuna and Alofi Islands), a Zone of Convergence in the Fiji Fracture Zone | Marc Regnier |
| 16:00-16:20 | Results of Geochemical Exploration of the Seafloor of Papua New Guinea | T. Kuriyama and M. Sakota |
| 16:20-16:40 | Research Activities at the Marine Minerals Technology Center, University of Hawaii | Michael J. Cruickshank |
| 16:40-17:00 | Operation of a Small Open-Cycle Ocean Thermal Energy Conversion Experimental Facility | Luis A. Vega |

## *Tuesday 5 October*

| | | |
|---|---|---|
| 08:30-09:00 | Assessment of Environmental Impact of Deep Sea Mining: Ecologic Studies of a Manganese Nodule Field in the Peru Basin | U. Von Stackelberg |
| 09:00-09:20 | Geothermal Development Potential of the Pacific Island Nations Situated Along the Pacific "Ring of Fire" | Harry Olson |
| 09:20-09:40 | Variations in Types of Geothermal System with Geological Setting Around the Pacific Rim | J.V. Lawless |
| 09:40-10:00 | Gold Mining at Vatukoula, Viti Levu, Fiji | Rod Jones |
| **10:00-10:30** | **MORNING TEA** (sponsored by Emperor Gold Mining Co Ltd) | |
| 10:30-11:00 | The Geology and Mineralisation of the Waisoi Porphyry Copper Deposit, Fiji | P.D. Ellis |
| 11:00-11:20 | Mt Kasi High-Sulphidation Alteration and Gold Mineralization, Vanua Levu, Fiji | G.J. Corbett and G.P. Taylor |
| 11:20-11:40 | The Papuan Ultramafic Belt Arc Complex | R. Rogerson, L. Queen and G. Francis |
| 11:40-12:00 | Geology of Amanab, Papua New Guinea | Stevie T.S. Nion |
| **12:20-13:30** | **LUNCH** | |
| 13:30-14:00 | Results from the Australian-Supported Evaluation of Petroleum Potential in Unfashionable Philippines' Basins: Lessons for Petroleum Exploration in the SOPAC Region? | Chao-Shing Lee, Malcolm C. Galloway and Neville F. Exon |
| 14:00-14:20 | Structural Evolution of the Aure Fold Belt, Offshore Papua New Guinea: Implications for Hydrocarbon Potential | Jon A. Rodd, Timothy Buddin and Francis Advent |
| 14:20-14:40 | Petroleum Provinces of the Solomon Islands | Bill Barclay |
| 14:40-15:00 | Use of Computers in resource Assessment - an Example from Solomon Islands in Hydrocarbon Evaluation | N. Biliki and J.A. Rodd |
| **15:00-1530** | **AFTERNOON TEA** (sponsored by Emperor Gold Mining Co Ltd) | |
| 15:30-16:00 | South Pacific Petroleum Survey - a Major New Initiative for Exploration of the Region's Oil and Gas Resources | Jon A. Rodd and Bill Barclay |
| 16:00-16:20 | Developing Standards for Measuring Coastal Changes in the South Pacific Region to Assess Vulnerability to Climate Change | Rick Gillie |
| 16:20-16:40 | Aggregate Investigations on Small Tropical Limestone Islands | D.R. Tappin |

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| 16:40-17:00 | Holocene Ocean Surface Temperature Variations in the SW Pacific Derived from Coral Sr/Ca Thermometry | J. Recy, W. Beck, F. Taylor, G. Cabioch, L. Edwards |
| 17:00-17:20 | Application of the IPCC Common Methodology for Assessing Coastal Vulnerability to Sea-Level Rise in South Pacific Nations Under the US Support for Country Studies | Rick Gillie |
| **17:20-19:30** | **DINNER** | |
| 19:30-22:00 | Working Groups | |

## POSTER PRESENTATIONS

| | |
|---|---|
| The Rifting of the Tonga/Lau Ridge and Formation of the Lau Backarc Basin: The Evidence from Site 840 on the Tonga Ridge | D.R. Tappin |
| HMR1 Survey of the Western Woodlark Basin, PNG | Brian Taylor, R. Hey, F. Martinez and A. Goodliffe |
| Results of Leg 2 - SOPACMAPS Cruise | Jena-Marie Auzende |
| The PACMANUS Hydrothermal Field, Bismarck Sea, Papua New Guinea: an Update | R.A. Binns, S.D. Scott and Shipboard Party |
| Preliminary Results of SOPACMAPS Cruise (Leg 1) | Jacques Daniel |
| Results of Geochemical Exploration of the Seafloor of Papua New Guinea | T. Kuriyama and M. Sakota |
| Groundwater Resources in Fiji | John Lewis and Prem Kumar |
| Papua New Guinea Geological and Earth Resources Information System: 'GERIS' | L.D. Queen |
| Shallow-Water Kuroko-Type Mineralisation in Fiji | D.P. Reddy and H. Colley |
| Hazards Map of the Circum-Pacific, Southwest Quadrant | R.W. Johnson |
| Return Periods of Large Earthquakes in Papua New Guinea | I.D. Ripper and H. Letz |
| Littoral Erosion of the Coral Island of Amedee Lighthouse, New Caledonia, Southwest Pacific | M. Allenbach |
| Holocene Evolution of the Rewa Delta, Fiji | Jared Armstrong and Graham Shorten |
| Status of NASA Aircraft Radar Measurements of the South Pacific Region | Donald R. Montgomery |
| Coastal Erosion Investigations at Yanuca Island and Cuvu Harbour, Fiji | Satish Prasad |
| Volumetric Model of the Monasavu Lake, Viti Levu, Fiji | Robert Smith |
| Morphostructural Study of the Southern Ends of New Caledonia and the Loyalty Ridge: Preliminary Results of the ZoNéCo 1 Cruise | G. Pautot, Y. Lafoy, J. Dupont, R. Grandperrin, C. Henin & "L'Atalante" Party |

## *Late Contributions:*

### CRYSTALLINE BASEMENT AND COVER RELATIONS IN THE AMANAB AREA, NORTHWESTERN PAPUA NEW GUINEA

S. Nion, R. Rogerson, M. Cussen, D. Hilyard, D. Holland, R. Sumaiang, A. Wangu, L. Joseph and D. Loi

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The Amanab 1:100,000 geological sheet area is located near the northwestern edge of Papua New Guinea, at the border with Indonesia. It is bounded by latitudes 3°30'-4°00' and longitudes 141°00'-141°30'. The area is within the New Guinea Thrust Belt, and immediately south of the Bewani-Torricelli Fault Zone.

Metadiorite and metagabbro of mid Permian and earliest Jurassic Amanab Metadiorite is basement to the area. It consists of more than one unit of variably deformed and altered metadiorite and metagabbro intruded by Paleocene dykes. It is a complex of at least two and possibly three undifferentiated intrusive units, which are overlain structurally by cover metamorphics and Mio-Pliocene Units.

Cover metamorphics consist of meta-sedimentary schist-grade Landslip Metamorphics, Ok Binai phyllite and early Tertiary slate-grade Wabia Beds. These same three units have been recognised 100 km further south in the Sepik River headwaters and the Wabia beds, in part, resemble units of the hemipelagic Port Moresby Association.

The Mio-Pliocene sedimentary sequence is in probable structural contact with the metamorphics. The basal part of the Mio-Pliocene sequence consists of Early to Middle Miocene Wogamush beds. Volcanolithic conglomerate, sandstone and minor volcanics dominate the Wogamush beds. Geochemical analyses of the volcanic facies suggests it ranges from probable arc tholeiites to more evolved calc-alkaline magmas.

The N17-N21 Orubadi and Wewak beds, which consist of sandstone, siltstone and mudstone, with frequent micrite interbeds, conformably and gradationally overlie the Wogamush beds. These units appear to reflect an up-sequence change from neritic to bathyal deposition. Locally capping the Orubadi and Wewak beds are Pliocene to Pleistocene unsorted slumped deposits of the Wosera Beds.

The structure of the area is strongly controlled by the east-west trending and gently northeast dipping New Guinea Thrust Belt. Crystalline basement discovered in the area is the most northerly in the New Guinea Orogen in PNG but it is not known whether it is contiguous with basement to the foreland Fly Platform 250 km to the south. Contacts between basement and cover and between cover metamorphics and Mio-Pliocene sediments appear to be structural and are probably low angle north dipping thrusts. Locally, prominent thrusts are broadly arcuate and plunge gently south. Some high angle ?normal faults also occur between metamorphics and Wogamush beds. Mio-Pliocene and younger units dip gently to the north parallel to major thrust planes.

Resource potential includes alluvial and hard rock gold, and hydrocarbons. Alluvial gold, derived from quartz-pyrite veins within the metadiorite and metamorphics, has been reworked from basal Miocene sediments by the present drainage. Production by local villagers is low mainly because of lack of infrastructure and incentives.

Although potential hydrocarbon source rocks are present in mainly Pliocene units, they are immature and lack suitable reservoir rocks. In the absence of pinnacle reefs, attention has been drawn to fractured carbonates or hanging wall anticlines as potential reservoir/traps.

## MORPHOSTRUCTURAL STUDY OF THE SOUTHERN ENDS OF NEW CALEDONIA AND THE LOYALTY RIDGE: PRELIMINARY RESULTS OF THE ZONÉCO 1 CRUISE

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(no abstract received)

## HOLOCENE OCEAN SURFACE TEMPERATURE VARIATIONS IN THE SW PACIFIC DERIVED FROM CORAL SR/CA THERMOMETRY

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