CORAL COLONIES AS MONITORS OF CHANGE IN RELATIVE LEVEL OF THE LAND AND SEA: APPLICATIONS TO VERTICAL TECTONISM

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ABSTRACT

Coral colonies living in very shallow water often act as precise recorders of changes in relative level of land and sea. On the Vanuatu (New Hebrides) islands of Santo and Malekula, corals recorded (1) the geographic extent and amount of seismic uplift and (2) the years in which three formerly unreported seismic uplifts occurred. The amount and extent of uplift were determined by measuring the difference in level between dead emerged and the highest living corals of the same species. The number of annual-type skeletal growth bands accreted since partial emergence of coral heads revealed the years in which uplift occurred. North West Santo uplifted in 1974 ± 1 yr. probably in association with large earthquakes in December-January 1973-74. South Santo uplifted in both 1966 ± 1 yr and 1972 ± yr. These uplifts were probably associated with large earthquakes in August, 1965 and October 1971.

Coral studies, in conjunction with tiltmeters and precise leveling in the context of seismicity and neotectonics, can be a powerful tool for documenting vertical crustal movements. From these movements, one may infer details about the seismic ruptures, how lithospheric plates interact, and the role of this interaction in tectonic evolution of the earth's crust.

INTRODUCTION

The purpose of this paper is to show how studies of coral colonies can document vertical tectonic movements. In the Vanuatu (New Hebrides) island arc, corals have been used to determine (A) the geographic extent of uplift associated with earthquakes, (B) the amount of uplift at many points along coasts, and (C) the years in which uplift occurred in past decades. This paper presents a study in progress and emphasizes the principles rather than an interpretation of the results. It is likely that the approach illustrated in this paper can be applied to study vertical tectonism in many other areas where the earth's crust is deforming. A detailed knowledge of vertical movements obtained from corals can illuminate the relationships among plate interactions, seismicity, and tectonic evolution of arc-trench systems and other geologic settings. Vertical movements also may help answer questions about seismic recurrence intervals, and whether aseismic vertical movements are precursors of earthquakes. These problems have been considered especially with respect to the Japan arc (Fitch et al. 1971, Yonekura 1975).

A great deal of effort is being expended in attempts to use precise leveling, tiltmeters, and tide gauges to measure vertical movements and deformation. Corals may record vertical movements in the recent past that are not possible to recover by other means.

In this paper the examples of tectonic information derived from corals come from the central Vanuatu islands of Santo and Malekula and nearby isles. These islands occupy the frontal arc between the volcanic chain on the east and the plate boundary on the west where the Indian plate is thrusting eastward beneath the arc (Fig. 1). In the Santo-Malekula area are at least four arc segments or tectonic blocks that are generally being tilted eastward with uplift rates as great as 7 mm/yr in late Quaternary time (Jouannic et al. 1980, Taylor et al. 1980). Santo and Malekula islands lie in the southeasterly trade winds belt between latitudes 14.5° and 16.5° S. The average daily tidal range between MHHW and MLLW is a little less than 1 m. The maximum daily range during the year is about 1.5 m.

DESCRIPTION OF THE STUDY

GENERAL PRINCIPLES

Recovery of tectonic information from corals is based on changes in the highest level at which each

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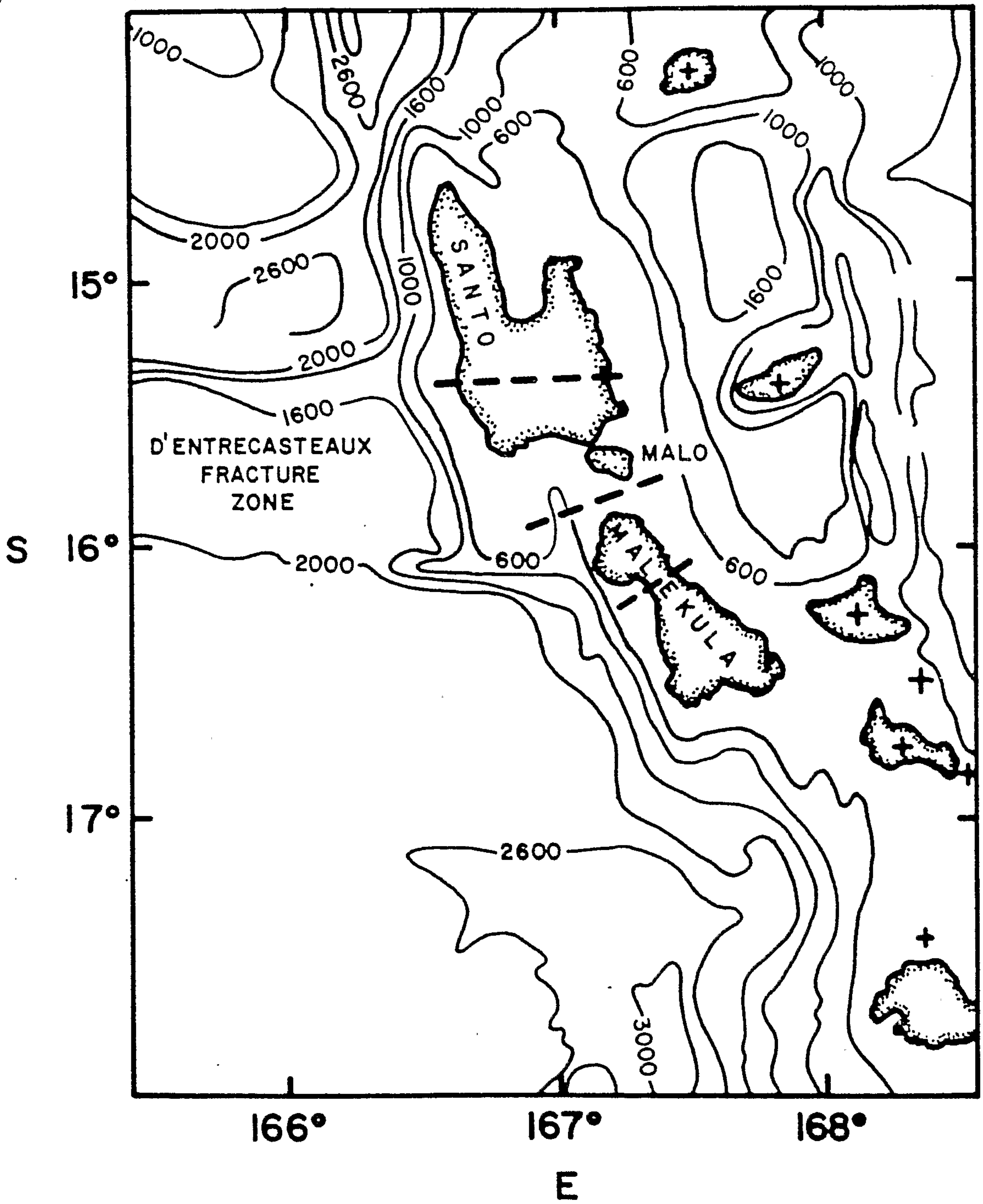


Figure 1. Bathymetric map of the central Vanuatu Island arc (14). A convergent plate boundary lies just west of Santo and Malekula although the physiographic trench seen in the north and south does not continue through the central part of the arc. The plus marks represent major volcanic centers. Across Santo and Malekula Islands and between, dashed lines represent tectonic tilt discontinuities documented by studies of emerged coral reef terraces (Jouannic et al. 1980, Taylor et al. 1980). The discontinuities divide the arc into blocks that are also related to seismic rupture zones and coseismic uplift patterns (Ebel 1980, Isacks et al. in press).

coral colony can survive and grow. This level, the highest level of survival (hls), is controlled by the degree of exposure of the coral during low tides. The hls varies with coral species, exposure to waves and other factors. Thus, each coral has its own hls. A group of corals may not share a consistent relationship to mean sea level. Rapid death of corals when sea level is lowered even temporarily has been demonstrated in the Middle East (Fishelson 1973, Loya 1976). On some coasts, corals rarely occur at their exposure-controlled hls, probably because of competition or other reasons, and thus, intertidal or shallow subtidal colonies may be rare despite a well-developed coral community a few m below sea level.

If a coral living at its hls emerges for any reason, the hls will be lowered and the corals or parts of corals higher than the new hls will die. A coral living at its hls on a coast which submerges may begin to grow upward to attain its new higher hls. Scoffin (1977) discussed the morphology of corals living in extremely shallow water. *Porites* sp. microatolls are good examples of corals growing at their hls for long periods. Microatolls of various species have already been used by others to document changes in the hls (e.g. Scoffin 1977).

The problem in using corals to study vertical movements is primarily one of interpretation. Studies of recent crustal movements need to be done in the context of deformation on longer time scales of 10^1 to 10^6 years. Some specific limitations on corals as monitors of vertical tectonism may include: (A) short term but significant vertical movements may not last long enough to affect coral growth; (B) it may be difficult to distinguish regional sea level fluctuations from vertical tectonism in some cases; (C) climatic variations from year to year could cause the hls to change.

Figure 2. Partially emerged *Goniastrea* sp. on the W coast of Malo I. The lower joint of the ruler is 6 in (15 cm) long. The hls of this coral head has been lowered twice so that only the lower right part of the coral was still living in July 1979. Figure 4 shows x-radiographs of cores drilled from the three stages of this coral.

MEASUREMENTS OF GEOGRAPHIC EXTENT AND AMOUNT OF EMERGENCE

Geological reports documented the association between uplift of Malekula Island and earthquakes in August, 1965 (Mitchell 1968, Benoit et al. 1971). In 1976, we began to measure the uplift, which was as great as 1.2 m, and to determine its geographic extent. All measurements of the 1965 uplift were based on corals killed by emergence (e.g. Fig. 2). The procedures and results were described by Taylor et al. 1980 and involved leveling from the highest living corals to the highest dead corals of the same species. Corals located in splash pools or on wide reef flats were avoided in favor of those adjacent to deep water. Dead and living corals with the morphology of corals living at their hls or in the shallowest possible depths were preferred (Scoffin 1977). At each locality we tried to make about 20 measurements of uplift to calculate a mean if enough appropriate coral colonies were available.

DETERMINING THE AGE OF EMERGENCE

It is important to determine not only how much, but when corals emerged. Corals on the coast of both NW Santo and S Santo appear to have been wholly or partially killed by emergence in recent years (Fig. 2). However, there are no geological reports and only contradictory local anecdotes about uplift in these areas.

It is not an acceptable hypothesis that the partially emerged coral heads used in this study were deposited on reef flats by storms. None showed evidence of having been rolled on its side, much less turned upside down. Nor are local changes in reef configuration or sea level acceptable explanations because the emergence varies systematically without respect to reef or coastal morphology. The areas of emergence are too local to be related to regional sea level variations. The excellent comparison between the recent coral emergences, the late Quaternary history of vertical movements (Jouannic et al. 1980, Taylor 1980), and seismicity strongly indicates that the coral emergence was tectonic.

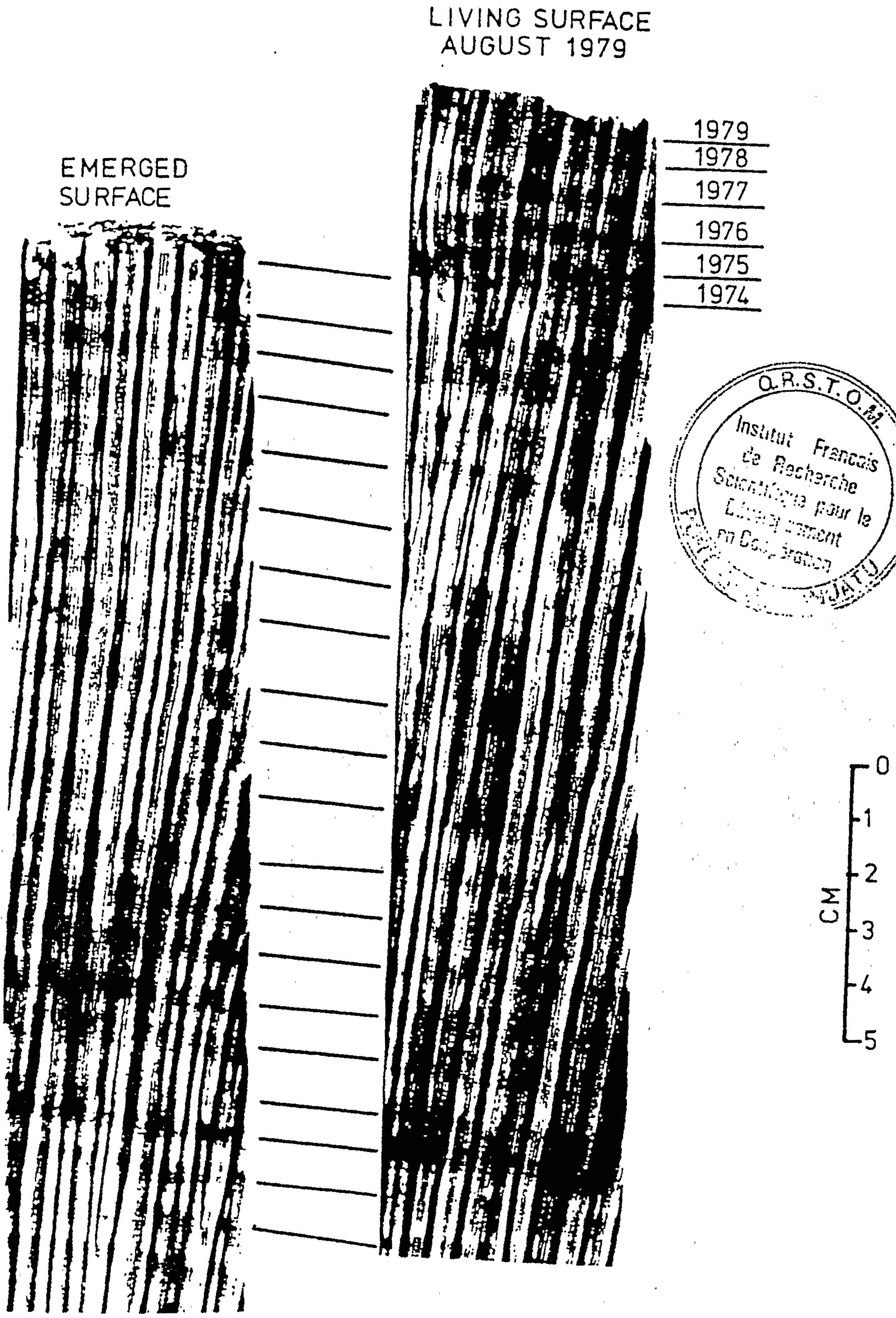
To discover when the corals in S Santo and NW Santo died, we investigated annual-type growth bands in the partially killed corals. We drilled cores from both the living and dead surfaces of the partially emerged corals. The cores were slabbed parallel to their growth axes and x-radiographs of the slabs were made (Dodge 1980, Weber et al. 1975). Cross-correlations of the slabs allowed counting the number of annual-type growth bands that had accumulated following partial death of the coral (Figs. 3 and 4).

Several assumptions are required for coral growth-band dating. Foremost is that each high-and low-density band pair represents one year of coral growth. This has been found in most studies (Knutson et al. 1972), although bands related to influxes of cold water (Hudson et al. 1976) and, perhaps, lunar periodicity (Buddemeier et al. 1975) have also been found. The dense parts of annual bands generally correspond to growth conditions that occur in the summer season (Weber 1975, Fairbanks et al. 1979). In Vanuatu the dense bands are usually deposited in the summer season (Weber 1975, Buskirk et al. 1981).

Figure 3, x-radiographs of a partially emerged coral from NW Santo, shows that about five band pairs accumulated between the times of partial death and coring in August, 1979. If each band pair represents a year, then the hls was lowered in 1974 $\pm$ 1. In December, 1973-January, 1974, there was a thrust-type earthquake sequence in the NW Santo area for which each of the three main shocks has a $Ms \geq 7.2$. No large shocks had occurred in this area for decades before 1973 and one has occurred since 1974 (Isacks et al. in press). It is likely that the lowering of the hls was due to uplift associated with the 1973-74 earthquakes.

Along the coast of S Santo and on Malo and Tangoa Islands off S Santo the hls of most larger corals was lowered twice in recent years (Fig. 2). Most of these corals were *Goniastrea* sp. heads located on a fringing reef flat an average of about 30 m from deep water. On the W coast of Malo, the coral heads show that each lowering was about 0.15 m (Fig. 2). X-radiographs of cores from the two emerged stages and from the living part of the Malo Island corals indicate that the hls changed 7 $\pm$ 1 and 13 $\pm$ 1 years before coring (Fig. 4). Similar results were obtained for corals from Tangoa island just off the central S coast of Santo. Thus, the corals emerged in 1966 $\pm$ 1 and 1972 $\pm$ 1. However, growth bands in a N Malekula *Porites* sp. coral show emergence only in 1965 $\pm$ 1. The older emergence was probably associated with the August, 1965 earthquakes whose rupture zone included S Santo and N Malekula. In October, 1971, a thrust-type earthquake $Ms \simeq 7.1$ occurred very near Malo Island. Considerably smaller shocks occurred near Malo in 1966 and 1973 (Taylor 1980, Isacks et al. in press). The most recent uplift of the S Santo area was probably associated with the largest of these shocks in October, 1971, 7 years and 9 months

Figure 3. X-radiographs of cores from the living and dead surfaces of a *Platygyra sinensis* coral head from NW Santo that was partially killed by emergence. The correlation is based on similarity of growth bands in the two cores. Between emergence and coring in August 1979, about five annual-type high-low density band pairs were accreted by the



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surviving coral. Thus, the emergence occurred in 1974 ± 1, probably in association with a sequence of large earthquakes near northern Santo in December 1973 – January 1974. The cores were drilled about 5 years, 7 months after the earthquakes.

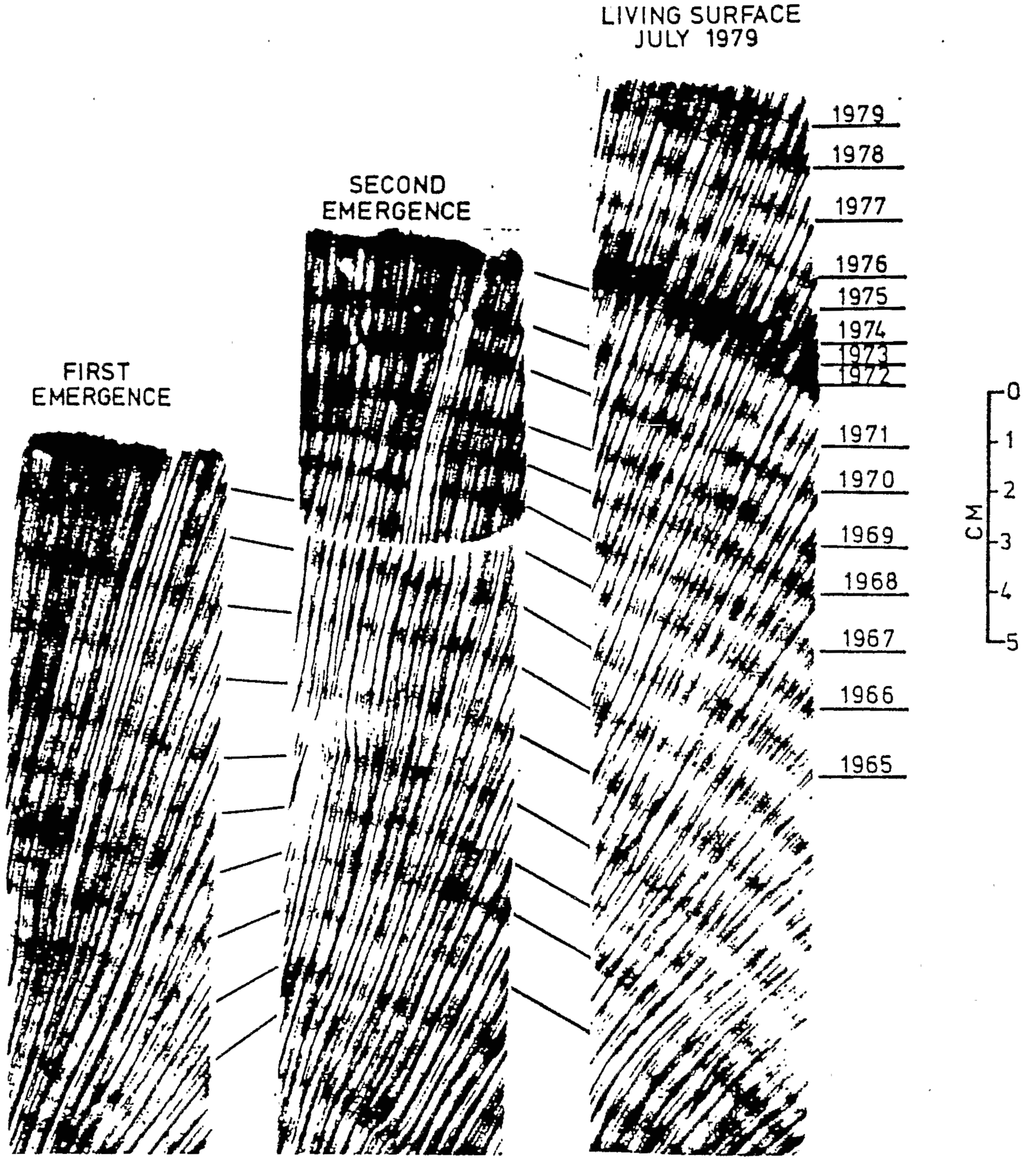

Figure 4. X-radiographs of cores from a *Goniastrea retiformis* coral head found on the W coast of Malo Island (Fig. 2). One core was drilled into living coral and two were drilled into dead coral that was killed by two different emergence events (Fig. 2). Correlations between cores are based on similarities in growth bands, including measurements of band widths. The band pairs designated 1966 to 1972 average 9 mm in thickness and those before 1965 average 11 mm in thickness. About 7, or possibly 8, annual-type growth-band pairs were added by the living corals since the latest emergence. If this emergence was associated with the October 1971 earthquake, then 7 years, 9 months elapsed between uplift and coring. Since the older emergence, represented by the core on the left, about 13 band pairs were added by the coral on the far right that continued living. Therefore, it is likely that the older emergence was associated with the August 1965 earthquakes.

before the corals were sampled. Because there was only about 0.15 m of emergence, the corals may have lived a few months to a year at a higher level before they died down to their lowered hls.

SUMMARY

The 1974 ± 1 uplift of NW Santo and 1966 ± 1 and 1972 ± 1 uplifts of S Santo provide new examples of uplift associated with earthquakes. Because S Santo and N Malekula were both uplifted in about 1965, but only S Santo was uplifted in 1972 ± 1 we better understand the relationship between seismicity and vertical tectonics in this area. N Malekula and S Santo may either share a seismic rupture and uplift as in 1965, or they may behave independently as in 1972 ± 1. Both inferences are consistent with details of the 1965 seismic rupture (Ebel 1965) and late Quaternary tectonic history (Isacks et al. in press, Jouannic et al. 1980, Taylor 1980). These discoveries require a reconsideration of possible seismic recurrence intervals for Santo and Malekula.

Corals record vertical movements over a time scale that is not possible for tiltmeters, tide gauges, and precise leveling. Although corals may not replace tiltmeters, the corals are already in place and recording. In conjunction with seismology and other means of measuring vertical displacements, coral studies can make a valuable contribution to documenting the details of recent vertical movements.

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