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The Late Quaternary Reefs

Guy Cabioch & Frederick W. Taylor

The Vanuatu island arc, at the convergent boundary of the Australian and Pacific plates, is characterized by some uncommon features in its central part. The central part of the Vanuatu arc is characterized by the absence of a physiographic trench where ridges and seamounts, the d'Entrecasteaux zone in particular, intersect the arc and are subducted. Moreover, the islands of Santo and Malakula occur anomalously close to the plate boundary and undergo rapid Holocene uplift rate up to 5.5 mm.yr^{-1} at south-west Santo and up to 3.4 mm.yr^{-1} in northern Malakula. Another characteristic is the presence of three parallel chains of islands:

- The western chain (Santo and Malakula);
- The central chain corresponding to active volcanoes (Aoba and Ambrym);
- The eastern chain (Maewo and Pentecost).

Eastern and southern Santo is covered by a series of raised reef terraces. The eastern part is topped by a broad reef plateau (Fig. 5). Several studies of these terraces have investigated various aspects of the island's neotectonics and paleoclimate.

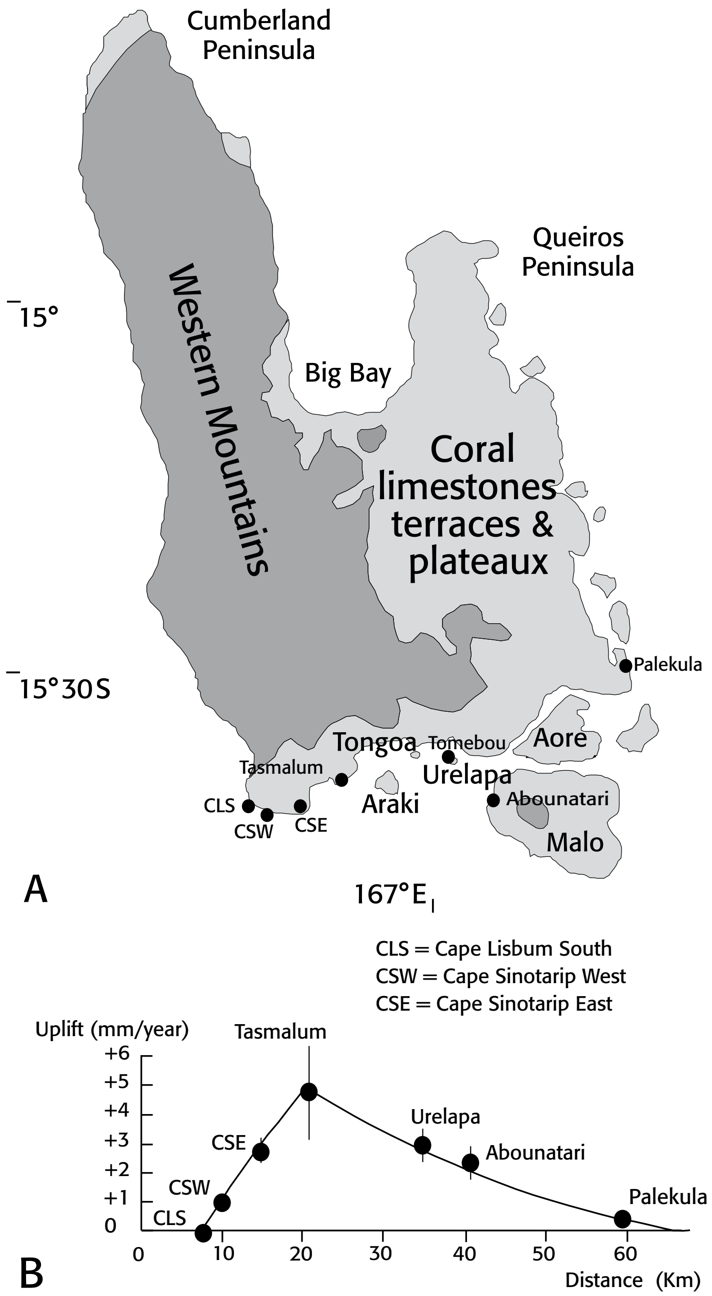

Figure 5: **A**: Location of uplifted coral reefs in Santo and location of the sites quoted in the text. **B**: Holocene uplift rates along the south coast of Santo (modified after Taylor *et al.* 1980).

NEOTECTONICS

Coral reefs can be used as recorders of neotectonic movements. (Fig. 7). Most previous studies devoted to coral reefs in Vanuatu were published in the 1970s and 1980s on this topic. In Santo, the uplifted coral reefs mainly occur in the eastern half of the island offlapping broad plateaux and in the south including the islands of Aore, Malo, Araki, Tangoa and Urelapa (Figs 5 & 8). The altitude of these terraces reaches a maximum of 784 m at Mt Tankara in the center of the island. Generally, their altitude increases to the west and reveals a tilting down to the east. The Holocene uplift rate displays a maximum of ~6-7 mm.yr^{-1} just west of Tasmalum and decreases both to the west and the east (Fig. 5).

Uranium-series and ^{14}C dating of both subsurface and surface samples provides information on the tectonic behavior recently analyzed and interpreted by Taylor and coauthors in 2005. Several sites from west to east were examined including Tasmalum, Araki Island, Urelapa Island, Tomebou Hill and Malo Island (Fig. 5).

At Tasmalum, the 6 ka (1 ka = 1 000 years) mid-Holocene reef flat is at an altitude of 35 m (Fig. 6A) indicating an uplift of 5.5 mm.yr^{-1}. Behind this reef flat, two corals from a terrace extending in altitude from 35 to 45 m are dated as 210.9 to 222.1 ka, (Fig. 6). The highest reef terraces behind Tasmalum, reaching about 400 m elevation, are thought to be in the 100-130 ka age range by correlation to dated localities on Araki Island, Malo Island, and southeastern Santo. This older reef corresponds to the interglacial sea level highstand called Marine Isotope Stage (MIS) 7c (216 ka) when

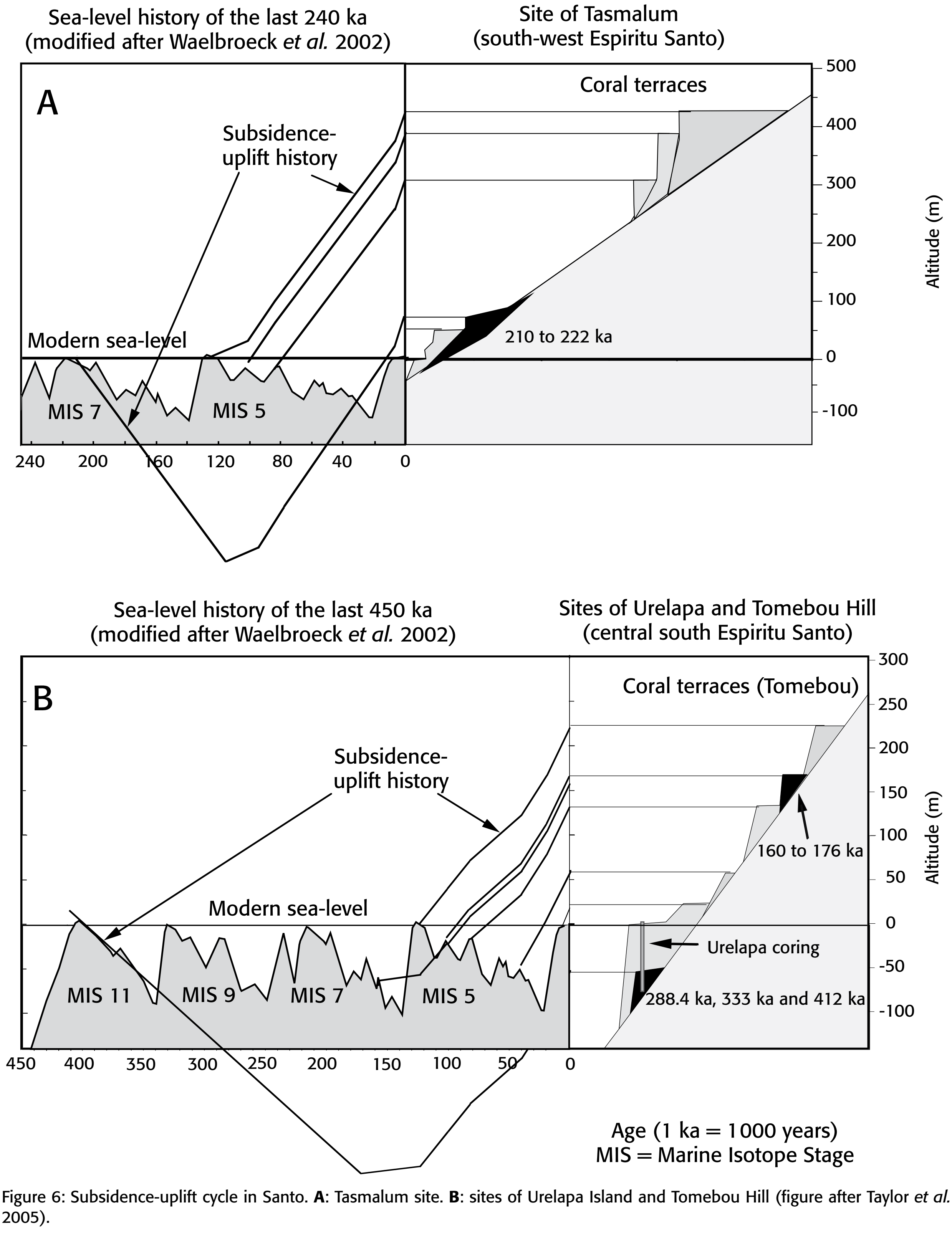

Figure 6: Subsidence-uplift cycle in Santo. **A**: Tasmalum site. **B**: sites of Urelapa Island and Tomebou Hill (figure after Taylor *et al.* 2005).

Figure 7: Porites microatoll, marker of sea-level providing evidence of uplifts.

sea-level was at an elevation similar to present. This reef grew before the younger MIS 5 reefs were uplifted to an altitude of 400 m. Taking in account that the MIS 7c and MIS 5 reefs formed at a sea-level similar to the present, the 216 ka reef must have subsided at least of 350 m by the time the MIS 5 reefs formed in order for them to now be separated vertically by 350 m. Such a succession is typical of a subsidence-uplift cycle.

Coral dating both in cores from Urelapa Island and Tomebou terraces which share a Holocene uplift rate of ~3 mm.yr^{-1}, reveals the existence of the last deglacial sequence (the last 23 ka) extending from +20 to -55 m (Fig. 6B). Below this sequence and deeper than 55 m, corals are dated of 288.4 ka, 333 ka and 412 ka at -58 m, -64 m and -75 m, respectively. The flanks and top of the 220 m flat-topped hill of Tomebou is dated of 37 and 38 ka at 41 m, 160 and 176 ka at 160 m and 149 ka at 220 m, respectively. The corals below the modern reef at Urelapa correspond to the MIS 9 to 11 (290 to 330 ka and 410 ka respectively). Assuming that these corals grew when sea level was in the 23 ka to present range of -125-0 m, then they have undergone a minimum subsidence of at least 150-300 m of these 300-400 ka reefs to explain their position below the modern reef and the occurrence of the 130 ka reef at +220 m. This scenario also supports the existence of cycles of subsidence and uplift.

Figure 8: Coral terraces from Araki Island, South of Santo.

These data indicate that Santo rapidly subsided at least once during the past 400 ka before being uplifted during the last 100-120 ka. This Late Quaternary cycle of uplift and subsidence occurs over one or two hundred thousand years. Subsidence and uplift of this large area on a 200 ka timescale might be explained by impinging seamounts and ridges that greatly increase friction between the subducting plate causing uplift. When the impinging objects break or are subducted, subsidence of the uplifted areas may follow.

THE MODERN REEFS

Studies of modern and living coral reefs in Vanuatu remain rare. In 1974, Guilcher analyzed the morphology of the coral reefs and defined the fringing and open-sea reefs as primary types. In 1990, Veron recognized about 62 genera and 296 hermatypic coral species in Vanuatu. In 1990, Done and Navin studied habitats of the shallow water communities of many coral reefs in different islands including Santo. From their study on reef zonation, they observed marked differences in the assemblages between the oceanic exposed reefs and the sheltered reefs and they recognized four typical assemblages:

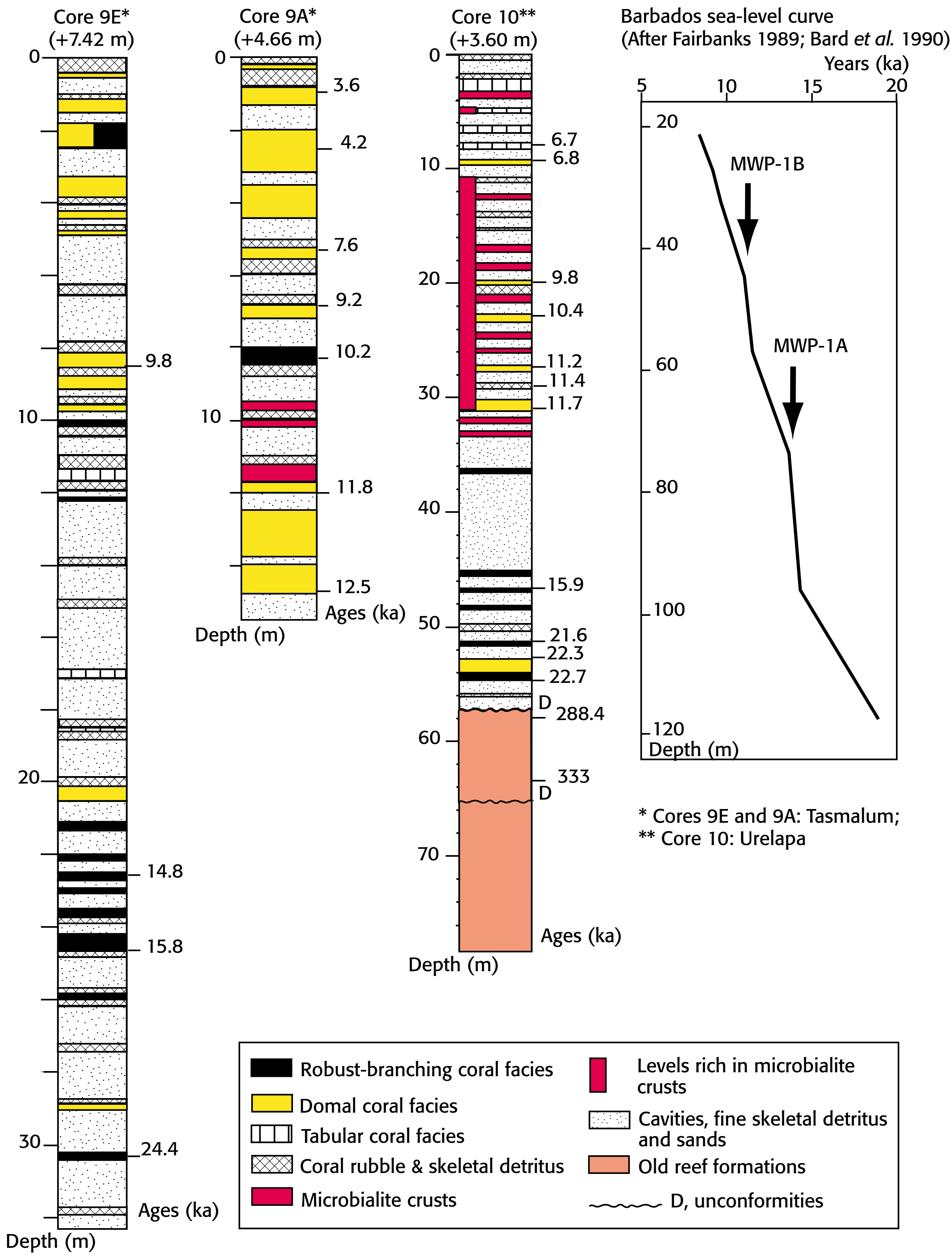

Figure 9: Biofacies of the 23 000 years old reefs from Tasmalum and Urelapa (adapted from Cabioch *et al.* 1998, 2003).

- In the outer reef slopes, the biological communities are characterised by abundant coralline algae and robust-branching corals (*Acropora* spp. and pocilloporids) in the reef crest zones and by massive and branching corals including *Diploastrea heliopora* and *Goniopora* spp. in the steep slopes.
- The sheltered parts of outer reefs are characterized by various species belonging to *Acropora* and *Montipora*.
- Open embayments are characterized by massive domal *Porites* spp. accompanied by *Acropora* spp.
- In the sheltered embayments, soft corals are dominant accompanied or not by domal *Porites* spp. Various branching forms of *Acropora* and *Porites* were also observed.

See also the chapter by Payri and coauthors in this volume.

REEF DEVELOPMENT DURING THE LAST DEGLACIAL SEA-LEVEL RISE (THE LAST 23 000 YEARS)

The modern coral reefs of Santo is primarily a result of their growth during the last 23 000 years. This period is marked by the sea-level rise from about -120 m to the present sea surface as a consequence of the melting of continental ice sheets in the polar zones. During this sea-level rise covering the last 23 ka, some brief periods of accelerated sea-level rise occurred (Fig. 9). These events, interpreted as accelerated ice cap melting are still debated, but are called meltwater pulses (or MWP) and observed at around 14 ka (MWP-1A) and 11.3 ka (MWP-1B). Species identifications of corals and coralline algae are used to reconstruct the succession of the past reef environments. The ecological significance of these organisms must be be inferred by comparison with their modern counterparts because their typical depth ranges vary in response to local ecological conditions particularly wave energy and irradiance.

In Santo, the growth of two modern reefs was investigated by drilling (see location in Fig. 5A). Several cores ranging in age from present to 24 ka were recovered in an oceanic exposed reef and a sheltered reef at Tasmalum and Urelapa, respectively. The Tasmalum area, in south-west Santo, underwent rapid uplift of 5.5 $mm.yr^{-1}$ (Fig. 5B). The modern fringing coral reef is narrow and characterized by reef fronts very close to the shores. Inland a series of several narrow and broad terraces bordered by more or less steep slopes terminate at an altitude of 35 m. At this altitude this terrace is the broadest and dated at 6.6 ka by Gilpin in 1982 and 7.1 ka by Bloom and Yonekura in 1985.

Offshore from the southeastern coast of Santo, Urelapa is an islet uplifted at a rate of 3 $mm.yr^{-1}$ (Fig. 5B). Urelapa is surrounded by a continuous narrow fringing reef characterized by steeply sloping forereefs very close to the shores.

The development of the Tasmalum reef is characterized by several stages (Fig. 9):

- A lower unit, from 24 to 15 ka, composed of fine skeletal detrital facies and robust-branching acroporids.
- A middle unit, from 15 to 10 ka, composed usually of a higher proportion of framework facies dominated by the robust branching assemblage indicating another shallowing up sequence.
- An upper unit, from 10 to 6 ka, dominated by a mixture of the robust branching assemblage with foliaceous corals typical of deeper waters. This unusual mixture of shallow and deep coral assemblages may be due to down-slope transport of corals during seismic events and, it appears therefore, that the robust-branching corals in this facies could be reworked. This may be a peculiarity of reef development on uplifting coasts. Another characteristic is the occurrence of microbialite crusts.
- From 6 ka to Present, reef growth is marked by a succession of emergence events resulting from the combination of sea-level stabilization and incremental uplift movements.

In cores drilled at Urelapa, the reef development is characterized by two stages as observed in the coralgal assemblages (Fig. 9):

- From 23 to 11.5 ka, by a branching coral facies of *Acropora* spp., various small coral buildups including favids, and encrusting coralline algae characteristic of medium to high energy conditions close to the sea surface.
- From 11.5 to 6 ka, by domal coral facies including *Porites* spp. accompanied by occasional branching coral forms, usually reflecting more sheltered habitats at 10 to 20 m depth. Occurrence of plan-laminar microbialites, especially abundant at the top of sequences, from around 12 ka to around 6 ka, provides evidence of reef growth in sheltered environments on relatively deeper slopes. The succession of two types of coralgal assemblages indicates a variation in growth mode, which can be subdivided into a keep-up growth mode from 23 to around 11.5 ka and a catch-up growth mode from around 11.5 to 6 ka. Such a change probably indicates global palaeoceanographic changes.

ROLE OF THE SUBSTRATUM IN THE INITIATION OF CORAL REEFS

At Tasmalum, reef growth initiated during the glacial period, older than 24 ka and probably as old as, at least, 30 ka, on a thick deposit of bioclastic sands and gravels rich in benthic foraminiferids, mollusc debris, and *Halimeda* segments. Then pebbles, gravels and conglomerates, encrusted by coralline algae, cap the thick sand formation.

At Urelapa, the substrate upon which the reef grew was reached only in the deepest cores at depths ranging from 60 m to 72 m and consists of recrystallized limestones rich in large benthic foraminiferids, calcareous algae and mollusks.

Such substrata both in Tasmalum and Urelapa have probably provided a favourable ground for reef initiation due to their roughness and carbonate composition which is know to be conducive to coral larval recruitment.

CONSEQUENCES OF THE RELATIVE SEA-LEVEL VARIATIONS ON THE MARINE HABITATS

In Santo, sea-level varied according to the eustatic variations and the tectonic vertical movements so that the modern marine habitats appear to be recent in terms of the geological time scale. During the last one million years, the high sea stands (interglacial periods), similar to the present sea-level, alternate with low sea stands (glacial periods) reaching more than 100 m deep at a cyclicity of 100 ka. Moreover, in combination with the vertical movements, comprising uplift and/or subsidence, the up and down movements of the coastline were amplified over time. In such conditions, the marine biodiversity probably benefited from such conditions in this island.