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TIME SPAN FORKARST DEVELOPMENT ON QUATERNARY CORAL LIMESTONES : SANTO ISLAND, VANUATU

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Abstract. – Santo Island, in the Republic of Vanuatu, is at the edge of the seismically active New Hebrides Trench. Quaternary eustatic sea-level fluctuations and coeval tectonic uplift have produced extensive emerged coralline limestone plateaus and terraces which have been karstified to various degrees. Radiometric ages and age extrapolation of titled coral reef terraces provide an age scale useful to evaluate the length of time necessary to develop various karst landforms. In fact, karst has only developed in Quaternary pure reefal limestones and is absent in Miocene to Pliocene calcarenites, thereby demonstrating that lithology dominates over time in karst development on Santo Island.

Conical karst features are predominantly related to fluvial erosion along structures. Terrace surfaces of last interglacial age (125,000 years) are characterized by solution dolines and nascent cone karst.

Between the last interglacial surface and the uplifted Holocene reef platform are narrow Wisconsinan interstadial terraces that show only minor karst relief. In contrast, the uplifted Holocene reef near the present coast is the site of extensive karst development. Large collapse features are associated with resurgences of groundwater near sea-level.

It is not possible to treat karst development in an inhomogenous limestone region under a general time-dependent scheme. The contrast between karst forms in the Quaternary limestones and their absence in Tertiary limestones show this limitation very well.

The occurrence of convergent landforms created by different processes requires caution about theories of time-dependent karst evolution. Karst forms in this tropical environment should be analysed with respect to their own individual geomorphic history in relation to facies differences, tectonic overprint, inheritance, and sea-level changes.

Résumé. – *DURÉE DU DÉVELOPPEMENT DU KARST SUR DES CALCAIRES CORALLIENS QUATERNAIRES : ILE DE SANTO, VANUATU.*

L'île de Santo (République de Vanuatu) est située sur le bord du fossé tectonique actif des Nouvelles Hébrides. Les variations eustatiques quaternaires du niveau marin et les soulèvements tectoniques concomittants ont provoqué l'émersion de larges plateaux et terrasses de calcaire corallien, karstifiés à différents degrés. Les datations absolues (radiométrie) et relatives (terrasses déformées) donnent une échelle de temps qui permet d'évaluer le temps nécessaire à l'apparition des différentes formes karstiques. En fait, la morphologie karstique ne s'est développée que sur les calcaires récifaux quaternaires, elle n'apparaît pas sur les calcarénites du Miocène au Pliocène, ce qui montre que c'est la lithologie, plus que le temps, qui est le facteur dominant dans le développement du karst sur l'île de Santo.

Les formes karstiques côniques sont surtout liées à l'érosion fluviale s'exerçant le long de formes structurales. Les surfaces des terrasses du dernier Interglaciaire (125.000 ans) sont caractérisées, elles, par des dolines (formes de dissolution) et des cônes karstiques coalescents.

Entre la surface du dernier interglaciaire et la plateforme récifale soulevée Holocène se trouvent d'étroites terrasses correspondant au Wisconsin, qui ne portent que quelques formes karstiques mineures.

Au contraire, au récif Holocène soulevé, proche de la côte actuelle, correspond une morphologie karstique importante. De grandes formes d'effondrement sont associées à des exsurgences de la nappe phréatique près du niveau de la mer.

Il est impossible d'analyser le développement d'un karst, dans une région de calcaires variés, dans un cadre général exclusivement basé sur le temps. Le contraste entre les formes karstiques des calcaires quaternaires et leur absence sur les calcaires tertiaires est une bonne illustration de cette contrainte.

L'apparition de formes convergentes modelées par des processus différents doit être prise en compte par les théories de l'évolution karstique qui la considèrent déterminée par le facteur temps. L'analyse des formes karstiques dans ce milieu tropical, doit tenir compte de leur histoire géomorphologique particulière, en rapport avec les différences de faciès, l'empreinte tectonique, les héritages et les changements du niveau marin.

Geomorphologists have always been interested in the time scale of landform development and the determining parameters for landform evolution. The perhumid tropical island of Santo (15° to 16°S lat.) offers a unique opportunity to investigate the development of karst landforms through time since coral limestone terraces of similar lithology but different ages occur in a uniform climatic regime which is not known to have varied significantly during world-wide climatic changes such as affected areas in higher latitudes during the Quaternary. Furthermore, the emerged terraces, whose ages are proportional to height, could theoretically show a sequential karst development similar to Grund's (1914) classic idea of cyclic karst development. If the cycle model had some application in reality, one should be able to observe a transition of increasing age from collapse doline karst through cockpits to cone and tower karst.

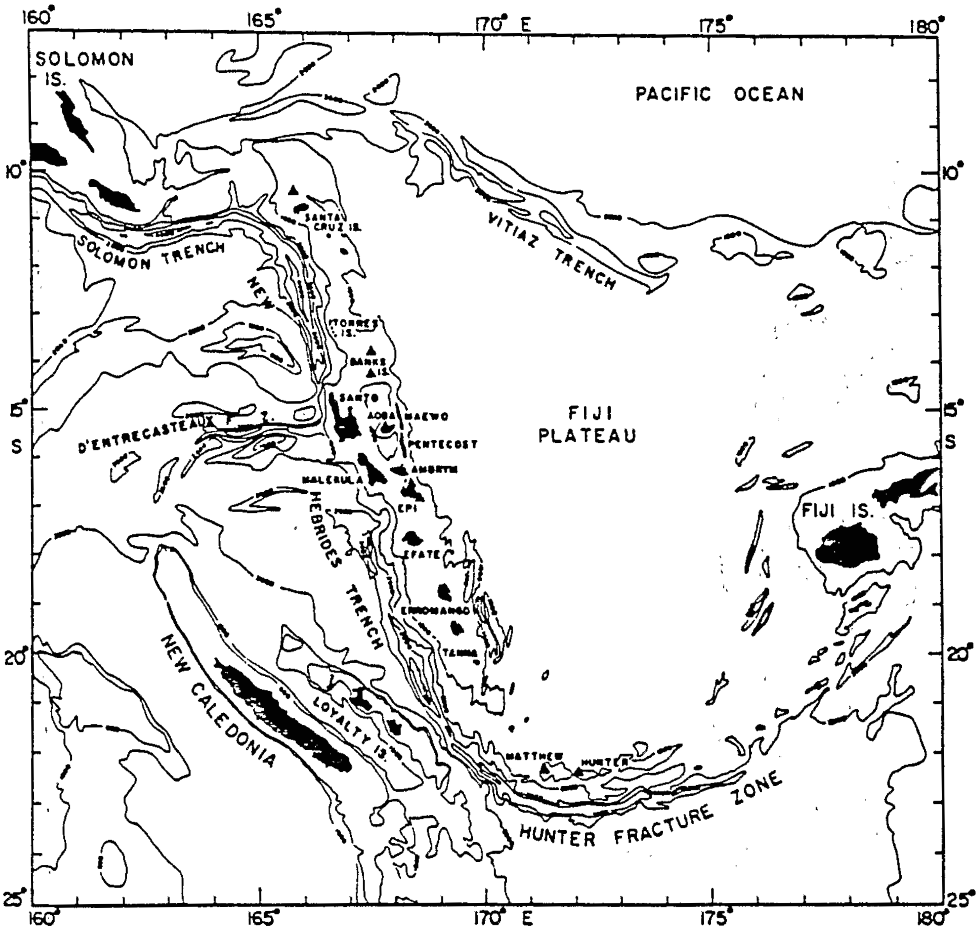

Fig. 1. – New Hebrides location map.
Fig. 1. – Carte de localisation des Nouvelles Hébrides.

Santo Island is at the edge of the seismically active New Hebrides Trench (fig.1). Due to the tectonic nature of Santo, coral terraces related to glacio-eustatic sea-level changes during late Pleistocene and Holocene time are constantly uplifted above modern sea-level. U/Th radiometric dates and age extrapolation with long-term uplift rates furnish an effective age control for most of the uplifted limestone terraces and plateaus. The pure Quaternary reef limestones comprise the East Santo Plateau limestones (fig. 2) and are in contrast with the middle Miocene to Pliocene Tawoli calcarenites which are characterized by a high degree of volcaniclastic impurities. The Eastern Plateau limestones are covered by an allochthonous soil cover of 2 to 10 m thickness and are characterized by a thick organic layer over a reddish-brown solum rich in 1/1 clays. The parent material is derived from volcanic ash falls of the Aoba and Ambrym volcanoes.

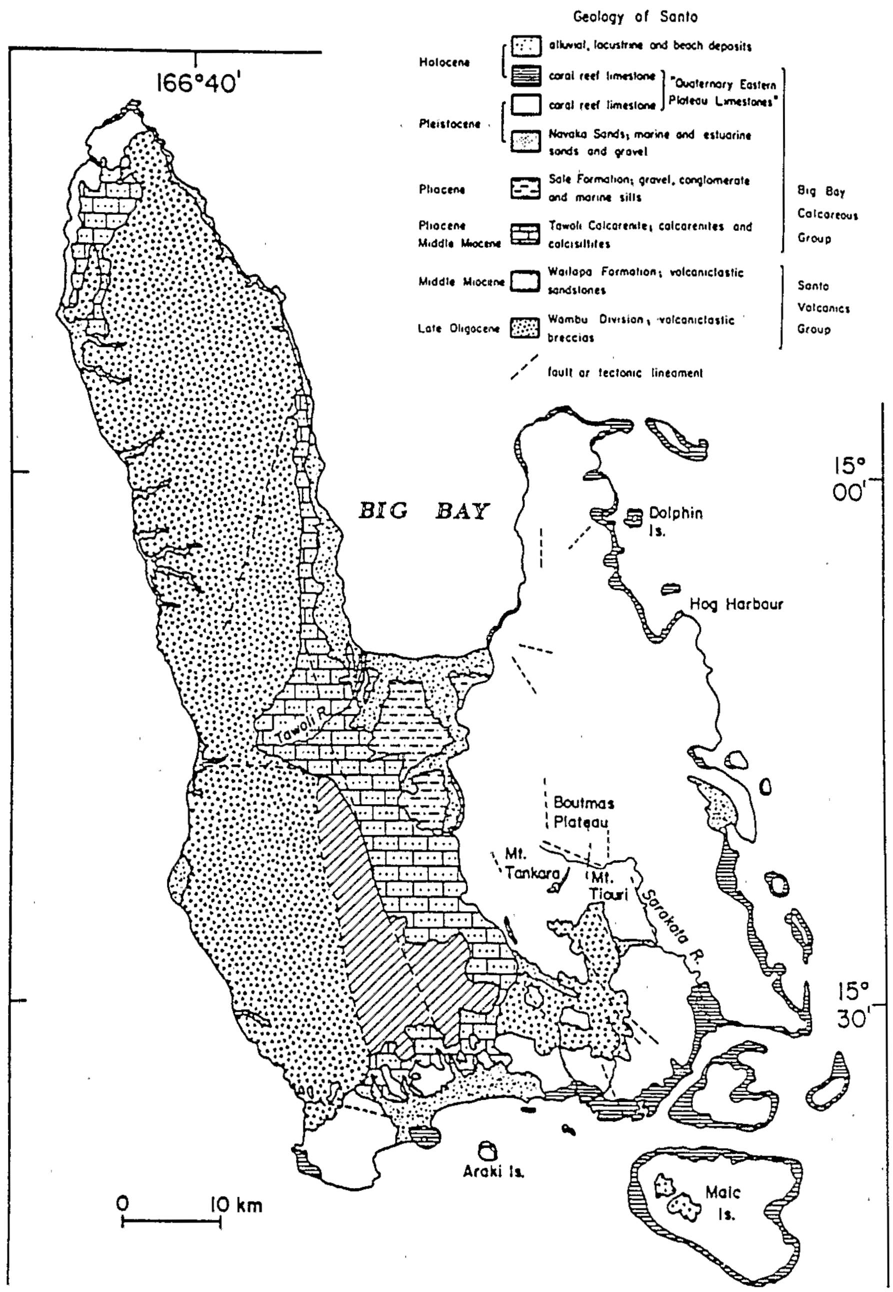

Fig. 2. – Geologic map.
Fig. 2. – Carte géologique.

The karstifiable reef limestones range in age between 1000 years B.P. to approximately 500,000 years B.P. U/Th dated aragonitic corals of reef crests define ages of 40, 60, 82 and 105 ka (1 ka = 1000 years) for phases of short-lived relatively high Wisconsin interstadial sea-level stands, and 125 and 149 ka for Sangamon interglacial high sea-level stands. The corresponding terraces of interstadial age are narrow fringing reefs, whereas the Sangamon interglacial terraces form a broad compound terrace surface, here termed the Luganville Surface. In contrast to the documented 28 ka interstadial reef surface in New Guinea, a corresponding terrace was not found on Santo, although uplift rates have been high. Instead, a broad Holocene reef surface extends seaward from the 40 ka terrace (fig. 3).

RESIDUAL KARST MORPHOLOGY ON THE OLDEST QUATERNARY LIMESTONES

The oldest Quaternary reef limestones include terraces and plateaus that are within an age range from the beginning of the last interglacial at approximately 149 ka back to about 500 ka for tilted limestone plateaus in the eastern center of the island at Boutmas Plateau, Mount Tankara and Mount Tiouri (fig. 3). In these locations, well developed conical hills have formed at former reef crests and along interfluve ridges on tilted limestone plateaus and terraces. The hills are typically 40 m higher than the adjacent former lagoonal back-reef environments. The extreme contrast is explained by the much larger area of solution in the back-reef environment than at the permeable reef-fronts. In the less permeable back-reef facies, calcareous muds are interlayered with calcarenites and calcirudites. The interstitial calcareous cement and thicker soils provide longer residence time for soil water and thus a higher degree of acidification with more effective limestone solution. The reef fronts, in contrast, are much more permeable and solution is minor. Shallow soils on the tilted reef crests do not permit a long process of acidification and waters may be less aggressive than in the back-reef areas. In addition, the CO_2 partial pressure in porous reef-crest facies most likely approaches atsmospheric values and thus any saturated solutions will precipitate $CaCO_3$ in or on the face of the reef crests. The result is protecting tufa curtains which enhance the topographic contrasts between reef crest and lagoon. However, conical hills have developed along the reef crests as a result of fluvial erosion perpendicular to the crests. Pure solution seems to be very limited, in contrast to published interpretations of conical karst hills on Jamaica. Conical hills caused by similar fluvial dissection occur in downdip direction on the tilted Boutmas Plateau and Mount Tankara. The overall tilt of the island caused surficial drainage patterns to develop on the back-reef facies and formed a topography of interfluve ridges and valleys. Like the reef crests, the interfluve ridges are dissected and the isolated remnants have a conical shape.

Only in a few locations are conical hills associated with typical over-deepening of solution dolines. One such place is the faulted limestone blocks at the northwestern end of the Boutmas Plateau, but even here erosion plays a major role in separating the positive relief into single residual hills. Other examples of solution-related remnants are to be seen in the interior of the tilted Boutmas Plateau, but due to the tilt, fluvial erosional forms dominate. At the Sarakata River, clusters of conical hills are surrounded by channels of intermittent creeks (fig. 3). The hills are most pronounced in close proximity to the local base level of the Sarakata River, suggesting that this is an example of fluviokarst mainly related to erosional processes. However, after heavy rainfalls many streams disappear in fissures or swallow holes and in other places depressions have formed in which thick accumulative soils promote vertical solution. This has created cockpit-like depressions around the hills which promote further solution. This is almost identical to Lehmann's (1936) interpretation of the Javanese Gunung-Sewu karst and represents two evolutionary stages : first, surficial drainage and fluvial processes, and later, a sub-surface system dominated by solution.

Pronounced residual limestone remnants occur only on the oldest Quaternary limestones, older than the last interglacial, and they are absent on younger terraces. It is interesting to note that karst is developed in the Quaternary limestones but is totally absent in impure Tertiary calcarenites that have well-developed fluvial valley networks. The lack of karst forms in the impure limestones is related to their high proportion of siliceous impurities and their greater mechanical strength. Thus, fluvial erosional forms dominate the relief in areas of impure limestones, whereas on the pure Quaternary limestones solution and erosional forms coexist. This also demonstrates that time is a subordinate parameter with respect to lithology if karst development is compared on terraces of different lithologic characteristics.

KARST FORMS ON THE LUGANVILLE SURFACE OF LAST INTERGLACIAL AGE

Features related to surface solution

The extensive Luganville Surface of last interglacial age (fig. 3) exhibits a variety of solutional topography. As on the older limestone plateaus, facies-related differential solution can be observed. The reefcrests at the terrace edges are always topographicaly higher than the terrace surfaces underlain by back-reef facies. But nowhere on the last interglacial surface has there been large scale dissection into residual conical hills.

By flying over the former largoonal environments and viewing aerial photographs the topography of the last interglacial surface can be seen to be a rolling hummocky landscape consisting of small solutional depressions and residual hills. However, the irregular back-reef surface is most likely related to the paleo-lagoon topography which is never smooth on living reefs. In fact, uplifted Holocene reef complexes in many islands of the New Hebrides Island Arc have a less pronounced but similar topography of small coral mounds and unfilled depressions and irregular channels.

The solutional depressions or dolines vary in depth from 2 to 4 m and are usually circular in map view. Thick clay-rich soils are typical for the paleo-lagoon surface. Soils that accumulate in the depressions stay moister than adjacent soils on hills. The relatively impermeable back-reef limestones and the thick soil cover cause standing water in the depressions after heavy rainfalls and create intense solution which overdeepens the depressions more and more, whereas the higher parts are less affected.

The rolling topography of rounded hills and depressions could therefore be interpreted as the initial or nascent stage of a cone and cockpit karst landscape, which in this case is related to overdeepening of preexisting depressions on the former lagoon floor which became solution dolines after subaerial exposure due to tectonic uplift.

Since the original setting of the paleo-lagoon is unknown it is impossible to determine how much limestone has been dissolved from the Luganville Surface. Trudgill's (1976b) micro-erosion rates of 0.11 to 12.5 mm/yr from a similar geologic setting on Aldabra Atoll may be used for an approximation. The Luganville Surface, which is about 125 ka in age, would have been lowered about 13 m in the case of an 0.11 mm annual denudation rate. The 13 m value compares favorably to the topographic contrast between reef crest and former lagoon floor. In contrast, an erosional rate of 12.5 mm/yr would have created relief that greatly exceeds the actual observed topography. It is therefore questionable to extrapolate fairly localized micro-erosion measurements through time. Most likely the overall denudation rate is even less than 1 mm/yr. Birot et al. (1958) and Stoddart et al. (1971) calculated 0.05 mm/yr removal of limestone in tropical environments. This would account for about 6 m denudation on a surface 125 ka old. Land et al. (1967) were even more conservative in suggesting a rate of 0.01 mm/yr for limestone denudation on Bermuda. Hopley (1982) reported solution dolines 1 m deep on a 125 ka old terrace on Barbados, and therefore confirmed slower long-term solution rates which are comparable to the calculations by Land et al. (1967). Because of the more humid conditions on Santo, deeper solution dolines and higher corrosion values can be expected, but rates much greater than 0.1 mm/yr seem unrealistic.

The Luganville Surface also presents an excellent possibility to evaluate the importance of climate in karst development, by comparing solution features on this surface with morphologic descriptions of karst relief on Barbados by Blume (1970) and Hopley (1981). On Barbados, no major positive karst forms are developed on terraces as old as 700 ka, but sinkholes and small cave systems are common. Sinkholes are deeper and more developed on the windward (wet) side of Barbados and on older terraces. Pronounced solution dolines have formed upon the 480 ka terrace, but the 125 ka old terrace of last interglacial age has almost no solution dolines more than 1-2 m deep. This difference from the Luganville Surface in Santo is striking because the reef limestones are similar and the ages are equivalent. The solution rates are greater on Santo because of a more humid climate. Barbados has an annual precipitation of only 1750 mm and has a dry season, whereas Santo has a perhumid climate with an annual rainfall of greater than 3000 mm for the regions of the Luganville Surface. Thus climate, soil properties, possibly paleo-reef topographic conditions and time are the main determining factors of solution doline development in a geologic environment like this. Santo also has a non-calcareous mountainous hinterland to provide allogenic runoff onto or under the limestone terraces, as discussed in the following section.

Collapse features

Associated with the shallow solution dolines and intervening rounded hills are collapse features with maximum depths extending to more than 150 m below the Luganville surface. There are also shallower collapse dolines not deeper than 10 m.

Collapsed features throughout the Luganville Surface are always associated with failure of roofing limestones over underground streams. These streams occur at various depths under the limestone cap. Because of cumulative uplift and Pleistocene sea-level fluctuations one would assume that rivers have adjusted to the repeated base-level changes by incising and stoping into the limestone. The result should be a high cavern system which could also explain the failure of overlying materials. This, however, is not the case, for conduits only of about 21 m height are seen at the bottom of collapse features as deep as 150 m. The streams emerge at the surface in front of a large terrace complex consisting of the Luganville Surface and attached minor Wisconsin age interstadial terraces. The point of resurgence coincides with the height of the predicted 42 ka terrace. Thus the subterranean river course is a very young feature which became established after the 105 ka, 85 ka, and 60 ka terraces had been formed and uplifted.

The advanced development of the larger dolines and river valleys is in striking contrast to Tricart's (1968) and Hopley's (1982, p. 193) ideas about karst on last interglacial surfaces. They reported poor karst development due to lack of joint development which does not allow concentrated underground water flow. Similarly, Hopley (1982) concluded that lack of jointing is responsible for the absence of caves and subsequent collapse features on reef limestones. He suggested that in general last interglacial limestones exhibit only surface solution features such as phytokarst forms reported by Folk et al. (1973) on Grand Cayman Island.

The formation of the collapsed valleys on Santo, however, may be related to the special setting of the Luganville Surface above Narango and Belmoul. Downward percolating waters in the extensive areas of back-reef facies are probably saturated with $CaCO_3$ in higher parts and are not able to dissolve large amounts of limestones anymore. The thick clayey soils and the poorly permeable back-reef limestones allow only a slow water percolation which means that acidified soil waters move very slowly through the rock and have sufficient time to dissolve great quantities of $CaCO_3$ in higher parts and reach the point of saturation. Thus, no pronounced cave systems are encountered. Therefore, one should not expect well developed collapse features in those limestones as predicted by Hopley (1982).

However, in Santo extensive allogenic river systems drain from volcaniclastic rocks in the mountainous island interior. The introduction of undersaturated waters from the mountains provides a powerful means to dissolve reef limestones along the contact with the volcanic rocks. Collapse features are most pronounced in those areas where streams from the volcanic basement enter the limestones (fig. 4). On the isolated plateaus of the Luganville Surface west of Hog Harbour, north of Port Olry and around the Walroul Plateau, collapse features are generally absent. Surficial solution features are well developed, however. These plateaus receive water only from direct precipitation and no outside source provides water for underground solution processes. This is probably also the reason that almost no collapse features are encountered on the much older Boutmas and Tankara Plateaus. Another important reason why collapse features are so pronounced in the southern region of the Luganville Surface is the conjunction of allogenic rivers with tectonic lineaments that cross through the Luganville Surface in a southeastward direction. Along the lineament trend the allogenic rivers were provided with paths of easier and faster penetration and solution so that extensive underground channels could develop. Vertical solution could proceed much faster along the disrupted limestones and account for their destruction. Such lineaments can be verified for the Rowa Rau and Wenoui Rivers, for example (fig. 2).

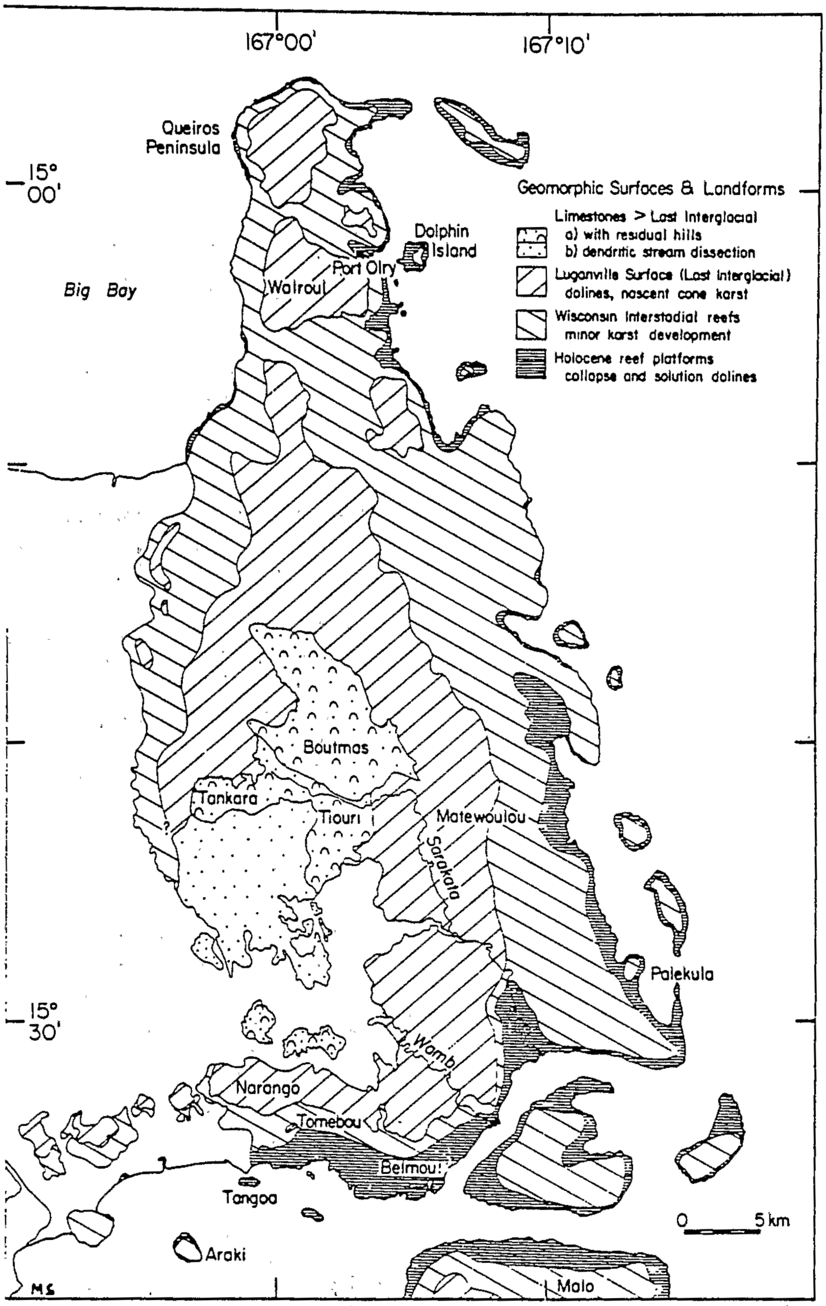

Fig. 3. – Santo physiographic provinces with different terrace levels.
Fig. 3. – Zones physiographiques de l'île de Santo ; terrasses de différents niveaux.

KARST FORMS ON THE WISCONSINAN (WURMIAN) INTERSTADIAL TERRACES

Due to the much shorter duration of the interstadials the related coral terraces are much narrower (fig. 3) and lateral changes of reef facies are not as pronounced as within the last interglacial surface with is characterized by deposits of two transgressions. Thus, the aerial extent of intense surface solution is very limited since the interstadial lagoonal deposits form very narrow terraces and minimum solution occurs in the permeable frontal reef. Other influencing factors are the thin cover of allochthonous soil and the paucity of autochthonous soil development which prevent long residence times and acidification of rainwater. Only small scale solution features occur in form of algal-covered spongelike limestone surfaces of the phytokarst as described on Grand Cayman island by Folk et al. (1973).

Solution processes, in conjunction with erosion, are more active where water runs down the reef fronts in small preexisting channels which are related to the grooves of spur and groove systems of the old reef. Purdy (1974) suggested that the spur-and-groove systems of modern reefs are most likely related to previous solution processes on the subaerially exposed reef. Therefore, in tectonically stable regions with coral reefs these features were etched into the coral reef during low stands of sea level and became submerged again as sea level rose. On Santo, solutional and erosional origin for the indented grooves can be denied since coral heads are found in growth position on the spurs and also towards the inside of the grooves. Also, on modern reefs at Santo these features are found and no link between preexisting solution features can be postulated since the reefs are younger than 6000 yrs. B.P. and have never been exposed to karst processes. Thus, the spur and groove systems are most likely not related to karst processes but their special constructional character enhances solution and erosion processes once they become subaerially exposed.

The interstadial terraces are also affected by collapse processes related to the same rivers that were described previously for the Luganville Surface. Due to collapse of the narrow interstadial reefs and parts of the upper Luganville reef-fronts the reef units become indented as, for instance, at the Wenoni and Wamb Rivers. In the case of the Rowa Rau River, where collapse is not yet complete, the water reappears at the surface through a resurgence in the vicinity of a terrace that is probably 60 ka old. There are numerous similar situations between the Wenoui and Adson Rivers, only on a smaller scale. These springs all have glass-clear water and only insignificant amounts of calcareous tufa are deposited at the point of appearance and in the subsequent surface channel. The apparent low degree of hardness is surprising if one considers that the water passed through an extensive limestone body. The consequent interpretation must be that these springs are resurgences of water that passes through the limestone body through fissures or swallets very quickly so that it does not become strongly acidified and limestone-aggressive. The only streams that disappear in swallets or fissures in this particular region are allogenic waters that sink into swallets on the Luganville Surface after short flow distances. The scarcity of similar springs below those segments of the Luganville Surface which are not receiving allogenic drainage corroborates the interpretation that the springs are resurgences related to sinking of allogenic streams on the Luganville Surface.

KARST FORMS ON THE UPLIFTED HOLOCENE CORAL REEFS OF SANTO

Collapse doline karst

Collapse doline karst is found on surfaces that range in age from 1000 to 6000 years B.P. Extensive forms are found at Hog Harbour and further north along the east coast and south of Tomebou (fig. 3). The best developed doline karst is on the 2 km wide Holocene surface in the vicinity of the former military airfield at Matewoulou. The dolines are circular or elongate in shape and are 4 to 6 m deep. In most dolines the sidewalls are covered with debris from the collapse. Often blocks of debris 2-3 meters in diameter are lying at the bottom of the depressions. The collapsed origin of the depressions is therefore clear, especially because the collapsed material has well defined circular holes that can be called root lapies. The root lapies also indicate the intense solution processes related to the highly acidic soil moisture. However, the genesis of the collapse dolines is not related to intense vertical solution with subsequent horizontal water movement in the subsurface. Rather, the occurrence of dolines is determined by the flow of underground water courses that emerge as exsurgences at the piezometric surface.

Depressions of non-collapse origin

Depressions other than the extensive collapse dolines also occur on the Holocene surface but seem to have a different origin. The majority of these depressions are found between Mount Tomebou and Wamb River on a Holocene surface that is more than 3 km in width. The shapes vary from circular and oval to more elongated forms. Circular depressions have diameters ranging from 20 to about 150 m. The elongated forms have widths up to 100 m and are usually up to 300 m in length. One of them is 1 km long. Their depths range from 2 to 5 m and in contrast to the dolines at Matewoulou they always have very gentle slopes. Some of the deeper depressions are permanently filled with water, but the shallower ones hold stagnant water only after long periods of heavy rain. It is interesting to note that most of the depressions occur within a kilometre-wide strip parallel to the coastline.

In contrast to the Matewoulou dolines these depressions are not related to collapse over underground streams. The depressions, especially the circular ones, look more like solution dolines as to those found on the Luganville Surface. Also, none of the depressions that are accessible contains irregular coral-rock debris with root lapies that is typical of collapse dolines. Thus, on first sight, it would be logical to assume a solutional origin for the depressions. On the other hand, the very shallow depth of solution dolines on the much older Luganville Surface contradicts such an interpretation. Subaerial exposure for more than 100 ka on the Luganville Surface has produced depressions of only 2-4 m depth, so it is unlikely that the depressions on the Holocene surface are of pure solutional origin. In the previous discussion of limestone solution rates it was shown that a denudation rate of 0.1 mm/yr would be realistic for the climatic and lithologic conditions on Santo. If this rate is applied to the 5000-6000 year old Holocene surface between Mount Tomebou and Wamb River then solutional depressions should be only 0.6 m deep and should definitely not exhibit depths of 5 m. The similarity of lithology between Luganville Surface and the Holocene surface makes it unrealistic to argue for higher solution rates on the Holocene

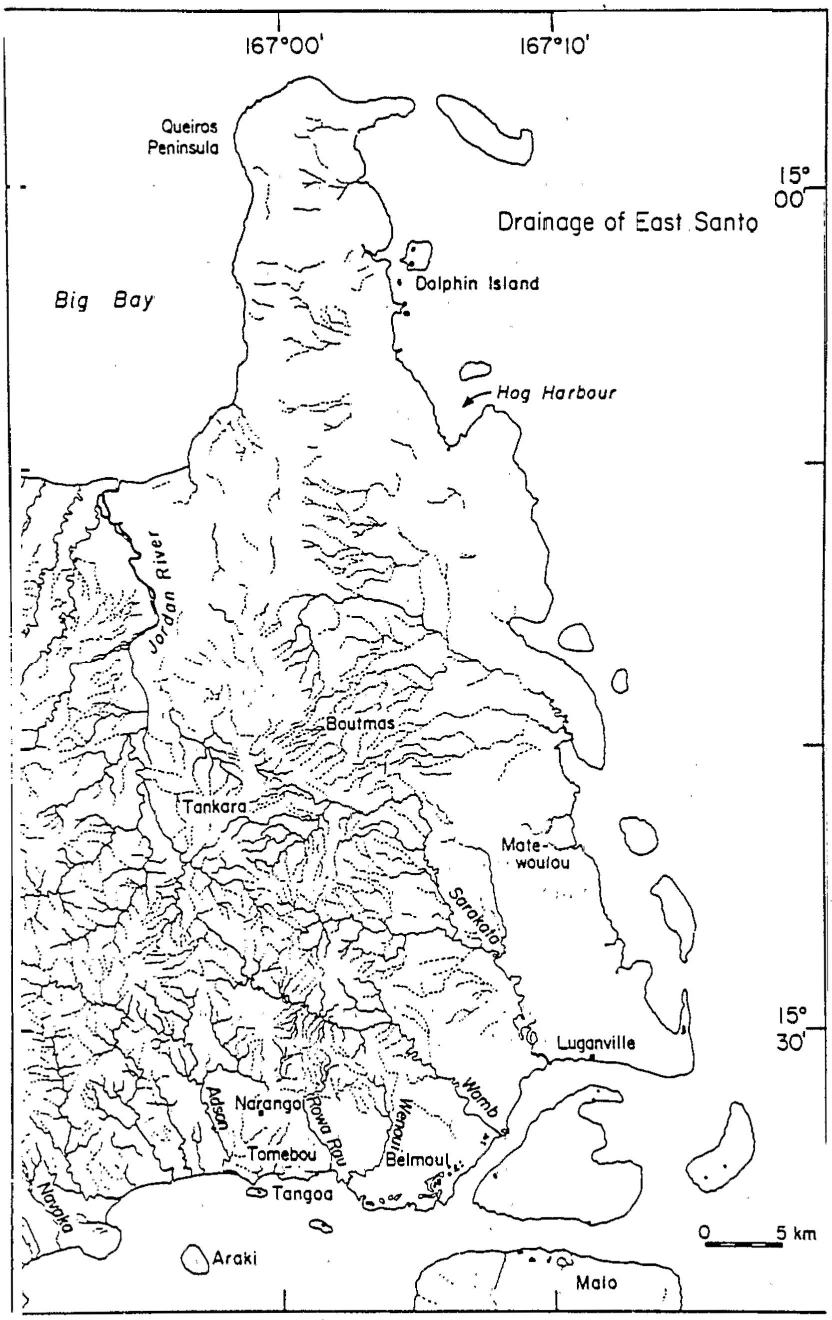

Fig. 4. – Drainage map of Santo.
Fig. 4. – Réseau hydrographique de Santo.

surface, since the limestones of both environments are characterized by lagoonal and back-reef facies. Of course, solution is very rapid on the Holocene surface since most of the primary carbonate is highly soluble aragonite, but the Luganville Surface had been in the same condition after it became emergent more than 100 ka ago. Also, major climatic changes during Wisconsin interstadials ans stadials are unlikely to have affected solution processes of limestone in the tropics, at least at these low altitudes. Taking all possibilities of intense solution into account it seems that the topography on this part of the Holocene limestones cannot be related to unique Holocene solution processes. Only two other alternatives are left then : either this topography is an inherited karst landscape in the sense of Purdy's (1974) antecedent karst or it reflects «premature» emergence of incomplete reef development.

The particular tectonic uplift and sea-level history for this part of Santo suggests that these features are related to the premature uplift of an incomplete reef over a broader and older surface which must consist of limestone since submarine karst springs are offshore from the Holocene reef surface. Holocene sea-level was never so low that this tectonically uplifted surface could have produced underground streams that would feed into the sea well below recent sea-level. We therefore conclude that this lowest limestone surface was an older reef that was overtopped by Holocene reef growth but was subsequently uplifted due to accelerated Holocene uplift rates. The older submerged reef or substrate is hypothesized to be the 28000 year-old terrace of the relatively high late Wisconsin Plum Point Interstadial sea-level. A terrace of the appropriate age has been documented in New Guinea, but has not been identified in the Santo chronostratigraphy. If it is buried under the Holocene reef, one can explain why the extensive Holocene reef surface could have formed in such a short time. Rapid tectonic uplift and a rising Holocene sea-level must have resulted in mainly vertical growth, and narrow ribbon reefs or small patch reefs would be expected. On a broad pre-existing surface, this area could have been rapidly colonized and a much bigger Holocene reef would have been the result. Due to increased uplift this reef growth could not be finished before it emerged and thus an incomplete reef was uplifted with a pseudokarst topography. One could argue that the incomplete reef growth only mimicks the older antecedent karst topography of the 28000 B.P. year old buried reef. We do not consider this to be likely because the depth, width, and shape of the depressions at Belmoul show no similarities with presently evolving collapse dolines on the Holocene reef at Matewoulou. The Belmoul depressions are much larger and preferred orientations with respect to the sea are not discernible.

Patterns of modern reef development, however, show much closer affinities with the depressions at Belmoul. A reef at Palekula shows the modern forms very well. At Palekula, the shoreline is defined by a well developed fringing reef at low tide level that has grown horizontally towards the sea. In map view the reef is undulating and has its maximum growth and areal extent in protrusions that occur at points where the island has seaward extensions.

About 200-300 m further seaward another shore-parallel reef is developing at lower depth as compared to the fringing reef. This elongated outer parallel reef can be subdivided into smaller crescentic segments whose backs have grown together whereas the downwind and shore-directed horns are either growing towards the fringing reef or evolve into circular growths around enclosed pools. The development of the outer reef created a segmented lagoon between itself and the fringing reef. Seaward protrusions of the fringing reef enclosed pools where they merged with the elongated outer seaward reef or its downwind horns. Most of the growth of the protrusions has been horizontal and the protrusions appear as submarine ridges. In the bay of Palekula they form reticulate growth patterns. Occasional single patch reefs grow between the protrusions and the leeward horns. The enclosed pools created by coral growth act as perfect sediment traps for coral debris, sand, and mud.

The shape of these lagoonal pools is similar to the Belmoul depressions. If it is imagined that a sudden increase in uplift exposed the reef at Palekula with associated termination of reef growth, the resulting topography would look like the depressions at Belmoul. In fact, pronounced tectonic uplift with 1500 year recurrence intervals is documented for this area. Depressions with seaward elongation at Belmoul can be compared and explained by analogy with modern pools created by seaward protrusion of fringing reef segments and their connection with an outer reef. Circular depressions can be represented by growth patterns observed at crescentic reefs. Not only the shape and orientation of the depressions in both environments are very similar but also their size. None of the pools is comparable in size and shape to the collapse dolines at Matewoulou. For this reason, the submarine karst-like topography is interpreted to be the result of reef growth patterns only. If the substrate had been considerably karstified it is postulated that one would see more small scale karst depressions with superimposed coral growth. This, however, is not the case. Since this submarine topography is so similar to the situation at Belmoul, the depressions at Belmoul are interpreted as correlatives to the enclosed lagoons in modern reefs at Palekula.

CONCLUSIONS

Radiometric ages for uplifted coral reef terraces and extrapolated terraces ages from longterm uplift rates provide a framework with which time dependent karst development can be studied in the perhumid tropical environment of Santo Island. However, a simple genetic time-dependent sequence of interrelated karst forms as in the classical karst cycle does not exist. Tropical karst features such as cone karst are best developed on reef surfaces that are 200000 to 500000 years old. Beginning stages of cone karst exist on last interglacial reef surfaces that are 125 to 139000 years old. In contrast to the observations of other workers in similar climatic and geologic environments, cone karst on Santo is neither predominately related to vertical solutioning in cockpits nor can it be seen as a result of intense collapse activity due to a fluctuating water table. Cone karst on Santo is related to surface fluvial processes in various geologic environments such as tilted limestone plateaus and along former coral reefcrests. It is only to a lesser extent associated with solution in cockpits. The nascent cone karst on the last interglacial Luganville Surface at Narango, for example, is related to solution origin alone. It also can been seen as a stage in an evolutionary sequence from pure solution dolines through nascent cone karst towards more pronounced features in some parts of the older limestones. This type of cone/cockpit formation is limited to lagoonal back-reef facies and demonstrates the different solution of reef facies. This, however, should not be misinterpreted as support for the cyclic theory of karst development since collapse features occur as well and there is no genetic interdependence between cone karst and collapse features. However, an evolutionary sequence different from the classical karst cycle can be postulated for solution dolines and cone karst on Santo. The genetic sequence for several cone karst occurrences on Santo begins with solution dolines and terminates with cockpits and cone karst due to overdeepening of the dolines by solution. In fact, the highest solution activity is concentrated in the former lagoonal environments. Solution rates of 0.1 mm per year can be deduced for these areas.

In contrast to the back-reef, the reef crests stand higher due to a greater degree of primary permeability and in later stages of development due to case-hardening and dripstone curtains. Thus, they are only slightly affected by solution. Conical and tower-like hills on reefcrests of limestone plateaus older than the Luganville Surface show that fluvial erosion and corrosion normal to the crests is more important than solution processes which play only a minor role in the final shaping of the dissected reef segments. In fact, the majority of positive karst features are undoubtedly fluvial erosion remnants. The landforms on Mt. Tankara, Boutmas Plateau, and Mt. Tiouri are good examples of such development.

The factor of lithologic control and its relevance to karst landform development becomes especially clear when the karstification of the Miocene Tawoli calcarenites and the Quaternary Eastern Plateau reef limestones are compared. Karst landforms exist only in the Quaternary reef limestones and are absent in the impure Miocene limestones. The lack of karst forms in the Miocene limestones is related to their high proportion of siliceous impurities and their greater mechanical strength. Thus, fluvial erosional forms dominate the relief in the impure limestones. On the Quaternary reef limestones, however, solutional and erosional forms coexist.

There are no simple sequential karst landforms on this tropical island. The different modes of occurrences of cone karst require that each landform must be interpreted in terms of its own individual geomorphic history. The positive landforms can be called convergent since almost identical landforms result from either structure – and lithology – controlled fluvial erosion or solution.

Time is a subordinate parameter with respect to lithology if karst development is analyzed in limestones of different lithologic characteristics. The contrasting morphologic development of the Miocene Tawoli Calcarenites and of the Quaternary Eastern Plateau Limestones shows this clearly. Among other parameters karst development within one single lithologic unit is also time dependent, which can be seen in the development of solution dolines within back-reef facies on the uplifted Quaternary terraces.

Collapse dolines on the Luganville Surface show the effect of several hundred metres of cumulative uplift and a lowered karst-hydrographic base level. Due to uplift throughout the time of the Wisconsin Glacial Stage and the Holocene, the terrace is now at about 200 m elevation. Subterranean streams flow under the fringing reef terrace at a depth of more than 150 m as indicated by collapse dolines over the Rowa Rau River at Narango. The alignment of the Rowa Rau River with a NW-SE trending tectonic lineament demonstrates the importance of tectonic movements upon the karst relief. The position of the island close to a convergent plate margin has resulted in differential tectonic movements since Santo came into existence. As shown by the Rowa Rau River, many tectonic lineaments define paths for preferential vertical and lateral solution in the limestones and have produced directed karst landforms. In fact, much of the fluviokarst on the high limestone plateaus is determined by the pattern of tectonic lineaments and the regional tectonic tilt of the island.

The formation of collapse dolines is less dependent on time than on solution doline development. Extensive collapse features exist even in Holocene limestones where subterranean water reaches the piezometric surface near the present coast. The lagoonal facies of these uplifted Holocene reefs are extremely unconsolidated. The predominate carbonate species is aragonite which implies that little solution and reprecipitation of calcitic cement has occurred. For that reason, the original reef-derived calcareous rubble, sands, and muds have low mechanical strength which leads to increased failure once subterranean channels have developed. A further result of low mechanical strength is that extensive cave systems cannot develop. The process of collapse is enhanced by frequent seismic uplift and large earthquakes that lower the karst-hydrographic base level and shatter the limestones.

A special case of interaction between tectonic movements and sea-level change is represented by the uplifted Holocene reef surface at Belmoul. An extensive area covered with depressions of irregular shape and various size suggests karstic origin. However, the topography can only be termed a pseudokarst since it is not related to recent or older karst processes. Unlike similar paleo-karst topography on the Great Barrier Reef in Australia this topography cannot be explained with the phenomenon of inheritance either. This special topography is related to recolonization of an earlier reef foundation that became inundated during the rapid early Holocene sea-level rise and was subsequently uplifted while still in a juvenile stage because of increasing tectonic uplift between 6000 and 4500 years ago.

In conclusion, an extensive karst relief on the Quaternary limestones of Santo is the result of facies-controlled lithology and purity of parent material, tectonic conditions, influence of soil and plant cover, Quaternary sea-level changes and the superposition of a perhumid tropical climate.

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QUESTIONS

Comment pouvez-vous expliquer la formation de dolines par des eaux allogènes, cette hypothèse semble insoutenable surtout lorsqu'on connaît la pluviométrie des Nouvelles Hébrides ?

Y-a-t-il une différence d'intensité de karstification suivant l'altitude ?

J. Bougère

– I have to reject your comment. We have ample evidence that the last interglacial terrace has large collapse doline systems only there, where the adjacent volcanic hinterland provides large amounts of allogenic runoff which enters the limestone cap and disappears in swallow holes and forms underground rivers. In some cases these rivers follow tectonic lineaments and, in one case a verified fault. This creates a type of «Karsthydrographische Wegsamkeit» (Lehmann) which facilitates sub-surface solution and the formation of large conduits which are sometimes 20 m in diameter. In front of the volcanic hinterland collapse occurs along these river courses and all intergradations, from aligned collapse dolines to entirely collapsed river courses with now superficially flowing streams, are found. In case of the Rowa Ran River, for example, the depth of the dolines is 150 m. The Rowa Rau reappears at the surface at the height of the 42 Ka terrace in front of the interglacial and older interstadial terraces, which demonstrates that the river course is a very young phenomenon which became established after the 105 Ka, 85 Ka, and 60 Ka interstadial terraces had been formed and uplifted above sea level. In contrast, in the northeastern part of the island occur isolated last interglacial limestone plateaus which receive water only from precipitation, the allogenic component is missing here and the pronounced collapse features which are typical for the southern part are absent.

It is interesting that Tricart (1968) and Hopley (1982) did not predict pronounced karst development on the geologically similar environment of Barbados Island (Antilles). The lack of caves and large collapse dolines on limestone terraces with similar ages to the Santo terraces was attributed to the absence of joint development which does not allow for concentrated underground water flow. Hopley (1982) suggested that on last interglacial limestones only surficial phytokarst would be found. However, on Santo the special hydrologic situation and the active tectonic behavior of the island account for pronounced karst development even on limestones of Late Pleistocene age.

– Karst forms are not related to altitudinal climatic effects in this setting. Precipitation at sea level and at 780 m elevation (where the oldest karst forms occur) is not significantly different that it could explain different karst forms. However, the more advanced karst forms in the highest limestone plateaus are explained by the long time of ongoing tectonic uplift and the resulting long exposure time to subaerial weathering processes. On the other hand, during the discussion of the Miocene calcarenites we have seen that altitude and age are subordinate factors with respect to lithologic control in karst development. Therefore, the differentiation into various karst forms on the Quaternary Santo limestones is the result of a complex combination of various factors including age, lithologic control, tectonic movements and the superposition of a tropical humid climate.

R.S.

M. Sweeting said she was much interested in this work ; Karst landforms on coral reefs and recent limestones are much more complexe than many people believe and much work has been focussed on this topic.

She asked if there was any evidence of case-hardening on the limestones discussed by M. Strecker.

M.M. Sweeting

We find evidence for case hardening mainly on the paleo-reef crests of the oldest tilted limestone plateaus in the central part of the island. After rainfalls the water has a short residence time in the very shallow reef-crest soils and enters the porous reef-crest facies. The CO_2 partial pressure in the air spaces of the reef-crest is probably close to atmospheric values and any carbonate containing solution will soon precipitate $CaCO_3$ within the reef crest or in front of it. This mechanism has created large Tufa curtains which actually protect the former reef crest from denudation.

R.S.

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par
Alain GODARD
en collaboration avec
Anders RAPP

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