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Giant dolines of the Muller Plateau, Papua New Guinea

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Abstract

The Muller Plateau lies within the Southern Highlands of Papua New Guinea, and is distinguished by its giant dolines. Many of these have exceptionally large dimensions and a morphology comparable to that of the megadolines of the Nakanai Mountains on New Britain and the tiankengs of the South China karst. They are all caprock dolines. The geology, physical geography and hydrology of the Muller Plateau are compared with those of the Nakanai Mountains and the South China karst. Proposed mechanisms for the formation of three groups (Rogorepo, Mamo and Atea) of giant dolines on the Muller Plateau are discussed. The Muller Plateau giant dolines, like the megadolines and the tiankengs, formed during the Pleistocene. The Muller Plateau dolines have formed in an environment that has many similarities to the other giant dolines. However, it is unlikely that they will ever evolve to the magnificence of the Nakanai megadolines or the aesthetics of the Chinese tiankengs, as a controlling factor in their development is a siltstone caprock and impure interbeds within the Darai Limestone.

Keywords: giant dolines, Muller Plateau, Papua New Gunea..

Introduction

Giant forms of karst features are rare and when found they are always subject to ranking for the record books. The Muller Plateau in the Southern Highlands of Papua New Guinea (Figure 1) has several giant dolines amongst its hundreds of smaller dolines. They are comparable to the tiankengs of South China and the megadolines in the Nakanai Mountains, New Britain, Papua New Guinea; these are referred to as megadolines in this paper, as that is the published name, though a strong case has been made to classify them as tiankengs (Waltham, this volume).

Both the Muller Plateau and the Nakanai Mountains lie in the tropics around 5ºS, and their geology and physical geography have many common features. These are compared to those of the tiankengs in the South China karst. The Nakanai Mountains and South China contain the greatest number of giant dolines in the World (Waltham, this volume).

The Muller Plateau lies on the southwestern slopes of the Muller Range, above escarpments 600-1000 m high 10 km west of the Strickland Gorge (Figure 1). A number of the Muller Plateau dolines have been identified as collapse features (Caffyn, 1974; James et al, 1976), and are believed to have formed in a similar manner to collapse dolines (Waltham and Fookes, 2003). These may be separated into two groups: those in carbonate rocks and those in non-carbonate rocks. The latter are less common and are called caprock dolines; the Muller Plateau giant dolines fall within the second group, while most megadolines and the tiankengs are in the first group (Zhu and Waltham, this volume).

Comparative geology

The rocks of the Muller Plateau are a marine sequence 1400 m thick that includes the Darai Limestone (Francis, 1980). This limestone consists of Upper Oligocene to Middle Miocene algal and forminiferal biomicrites. The overlying Lai

Formation is almost entirely siltstones and mudstones, whereas the underlying Ieru Formation is mainly fine-grained clastic sediment (Francis, 1980). The Yalam limestones of the Nakanai Mountains are younger, from Lower Miocene to Lower Pliocene. They vary from a compact and massive limestone, to a porous coral algal limestone and a well-bedded bioclastic limestone similar to chalk in colour, porosity and permeability (Audra et al, 2001). Their thickness varies between 500 and 1000 m (Löffler, 1977). A wide range of carbonate rocks, from Cambrian to Triassic, form the South China Karst (Yuan et al, 1998). They crop out as massive limestones, dolomites and dolomitic limestones, in a sequence up to 3000 m thick in Guizhou and Guangxi (Waltham, 2003). They had been uplifted to become part of the Eurasian continent before the marine sediments of the Muller Plateau and the Nakanai Mountains were deposited.

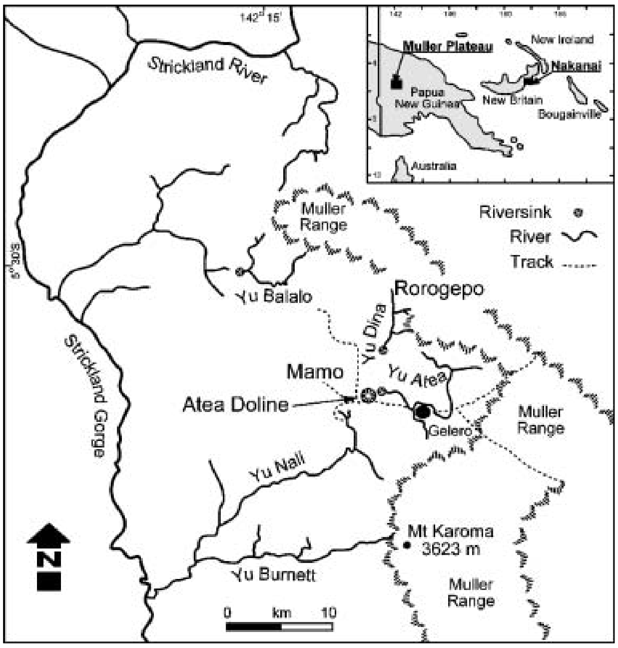

Fig. 1. Locations, within Papua New Guinea, of the Muller Plateau in the Southern Highlands and the Nakanai Mountains in New Britain. (Adapted from Montgomery, 1974)

Where the Darai Limestone has been exposed on the Muller Plateau by erosion of the Lai Formation, surface karst processes have led to a great variety of landscapes. In the Nakanai Mountains, the Yalam Limestone was covered by thick Pliocene volcano-sedimentary deposits (Audra et al., 2001). Since uplift these have been weathered and eroded, exposing the limestone and in places forming a poorly developed polygonal karst. In the catchments for the underground rivers, the thin beds of the volcanic cover act as a caprock limiting the penetration of seepage waters and collecting runoff (Audra and Hobléa, 2001). Erosion levels expose continuous limestone outcrops across large areas of the South China karst, and an impressive cone karst landscape has formed, though there are some areas covered karst with a thin and discontinuous caprock.

Both the New Britain limestone and the South China carbonates have been described as pure. In contrast, although some beds of the Darai Limestone are pure, there are numerous interbeds of impure limestone and calcareous clastic sediment (Francis, 1980). The limestone in China is strong and well lithified, while the Muller Plateau Darai Limestone varies in lithology between strong micrites and weaker, more chalky rock, and much of the Nakanai's Yalam Limestone is more comparable to a strong chalk. In all three areas, the limestones were deformed and uplifted in the late Tertiary and early Pleistocene Himalayan orogeny. As they were uplifted, they were folded, faulted and jointed - providing the fracture nets that allowed water penetration into the limestone and into major conduits.

Major surface rivers have cut into the three terrains, forming deep gorges and canyons. This rapid valley incision lowered the springs and deepened the vadose zones in the massifs by up to 1000 m. The deeply incised Strickland River and its tributaries such as the Yu Nali (*Yu* = *River*) are the main influences on the Muller Plateau karst (Figure 1). In all three areas, cave resurgences have become perched above major rivers, as the result of uplift and incision by the major surface rivers at greater rates than those of the smaller underground rivers. The Nakanai Mountains uplift is believed to be at the exceptionally rapid rate of 3 mm per year (Löffler, 1977). On mainland Papua New Guinea, it is slightly slower, at 2-3 mm per year (Gillieson and Spate, 1998). In South China, it has all but ceased (Yuan et al, 1998). However, all three areas still experience earthquakes, and the island of New Britain still has its active volcanoes (Audra, 2001a).

Comparative physical geography

Climate, vegetation and hydrology are all important as influences on the rates of cave development and surface denudation in these three karst terrains. The Muller Plateau dolines lie at elevations of 2000-3100 m, in a cool, highland, tropical climate (Löffler, 1977). Annual rainfall has been estimated at 3.5-4.5 m (James et al, 1980a); this could be a gross under-estimate, as the maximum recorded annual rainfall is 11 m at the

Ok Tedi mine, 150 km to the northwest and at the same altitude as the Muller Plateau (Gillieson and Spate, 1998). The Nakanai Mountains have a hyper-humid, equatorial, mountain climate with an extremely high rainfall estimated to be between 10 and 12.5 m (Audra, 2001b). The rims of the megadolines that contain rivers are at altitudes of 200-600 m, where the rainfall is much lower (Audra et al, 2001). The South China tiankengs are in the subtropics, and have a warm to temperate climate; most tiankengs have rims at altitudes of 1000-1500 m (Zhu and Chen, this volume). On the Muller Plateau, the annual means and wide range of temperatures are comparable to those experienced in South China (Yuan et al, 1998). Variations in South China are controlled by latitude and season, but the only temperature controls on the Muller Plateau are diurnal and altitude effects. The Nakanai Mountains have the highest mean temperature and a lower annual range (Audra et al, 2001).

Vegetation on the Muller Plateau ranges from a mixed tropical rain forest, through moss forest, to open clearings that contain shrubs and grasslands. The Gelero clearing (Fig. 1) in the Atea catchment supported a small population until the 1960s, and its vegetation is therefore the result of slash and burn agriculture. Other clearings remote from habitation or hunting grounds also show evidence of fire (Pybus, 1974). The Nakanai Mountains are covered by primary tropical forest (Audra et al, 2001). In these tropical areas, full forest vegetation can grow even on the steepest slopes and rock is only visible in occasional bluffs and where landslips have removed the plant and soil cover. At present, the tiankengs in China lie in a mixture of agricultural land and subtropical forest. In the past, there would have been subtropical forests inter-dispersed with grassland. In all three areas, climate and vegetation are ideal for the carbon dioxide production that is essential for limestone solution.

Comparative denudation rates are 400 $m^3\ km^{-2}a^{-1}$ for the Nakanai Mountains (Audra, 2001c), 200 $m^3\ km^{-2}\ a^{-1}$ (James, 1980) for the Muller Plateau. No values are available for the South China karst, they are quoted as high (Yuan et al, 1998; Zhu and Chen, this volume), but they are expected to be significantly lower than the tropical areas.

The development of a large cavern is an essential precursor to the creation of a giant collapse feature, and a subterranean river is a usual requirement for this. After collapse, the river has three further roles - to dissolve and remove carbonate breakdown, to mechanically erode and transport both carbonate and insoluble breakdown, and to continue to enlarge the cavity by basal sapping of the walls. The size of a subterranean river depends upon its catchment area, and the percentage of it that is on non-carbonate rocks controls its aggressivity.

On the Muller Plateau, the catchment for the Yu Atea is over 100 km^2, almost all of it on the Ieru and Lai Formations (Francis, 1980). This produces an estimated low flow of 4 $m^3\ s^{-1}$; high flows exceed 30 $m^3\ s^{-1}$ at the Atea Doline (James and Martin, 1980). The catchments on the Nakanai are harder to characterize because the outcrop ratio of the insoluble caprocks to bare limestone has not been recorded. The catchment for Muruk cave is about 20 km^2, and this produces a low flow of between 2 and 4 m^3s^{-1} at the Berenice resurgence (Audra and Hoblea, 2001). The rivers flowing through the megadolines have much greater low flows, estimated at up to 20 m^3s^{-1} (Audra et al, 2001). The river flowing through the Xiaozhai Tiankeng has a catchment of 280 km^2 (Zhu and Chen, this volume), composed of carbonates, sandstones and shales (Senior, 2003). The river has an average annual flow of 7-8 $m^3\ s^{-1}$ and has a maximum discharge of 174 $m^3\ s^{-1}$ (Zhao, 2001). These are accurate figures, as the water from this tiankeng is diverted to a hydroelectric power plant. The annual distribution of the river flows is also important. The Muller Plateau runoff is effectively constant throughout the year; it only requires the afternoon convective rains to raise the flow in the rivers because the soils and epikarst are permanently saturated (James and Martin, 1980). In the Nakanai Mountains and South China, the monsoon rains generate huge flows that are exceptionally destructive mechanical erosive agents (Audra et al, 2001; Senior, 2003).

The tiankengs in South China have floors surrounded or partially surrounded by vertical cliffs (Zhu and Chen, this volume). The cliffs may have pronounced ledges and breaks, leading to gentler slopes formed by the accumulation of wall breakdown and slope wash. Many tiankengs have a river across their floor or evidence of one flowing through their base; ideally, there are inlet and outlet caves in the tiankeng. Although many of the megadolines fit this description perfectly, there is a noticeable difference between these two giant collapse features. The tiankengs have large vertical cliffs of bare rock, while the megadolines have few bare cliffs but their walls are overhung or covered with vegetation (Audra et al, 2001). The giant dolines of the Muller Plateau only partially fit the tiankeng description, as they do not have rivers flowing across their floors.

The Muller Plateau

There are three notable groups of giant dolines on the Muller Plateau (Fig. 1), which are each distinguished by the details of their morphology and the mechanisms proposed for their formation.

The Rorogepo dolines

The giant closed depressions at Rorogepo form grassland clearings amongst the moss forest (Fig. 2). Since they have never been cultivated, it is probable that the grasslands are controlled by cold air drainage into the depressions and temperature inversions. The thinly bedded Darai Limestone that crops out in them has interbeds of impure limestone and calcareous clastic sediment. The Rorogepo depressions have rim diameters ranging from a few metres to over a kilometre; in many there are smaller depressions nested within the larger ones (White and Frank, 1980). It is unlikely that these are collapse features as they have gentle slopes and erratic shapes developed by the gradual removal of material by solution processes (Francis et al, 1980a). In the floor of one small doline, Uli Mindu is an unstable solution shaft 200 m deep that ends in a large rockfall chamber (Beck, 2003). Such enlargement at the base of deep shafts is common and results from wall breakdown. The process continues up the shaft until a doline forms inside a partial or complete ring of cliffs. Some have volumes of around 1M m^3 and have the appearance of tiankengs (Fig. 3), but have clearly evolved from solution shafts.

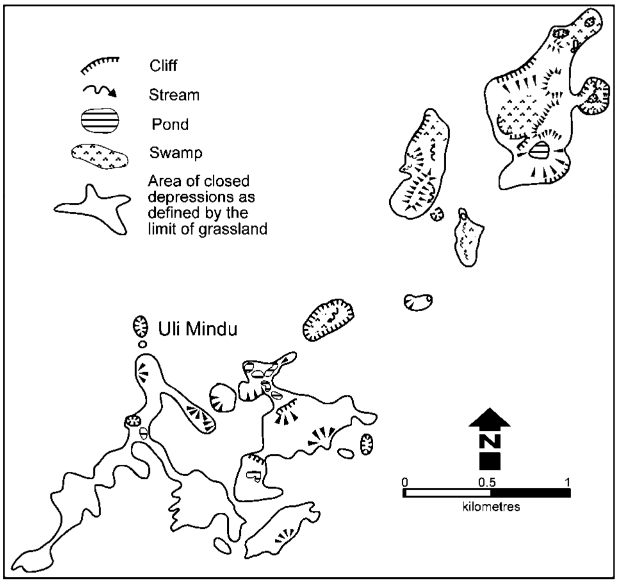

Fig. 2. Dolines of Rorogepo. (Adapted from White and Frank, 1980)

The morphological similarity between solution and collapse dolines arises from the lithology of the local Darai Limestone. With relatively strong and competent units of pure limestone inter-bedded with weaker units of impure limestone or calcareous clastic sediment that are less permeable, seepage waters commonly issue from the contact between a pure limestone and the underlying less permeable bed. This gives rise to basal sapping of the competent units and consequent rockfalls. Exposed faces around shafts and dolines retreat by this method, and maintain their steepness over time. Under these circumstances, even dolines that are initially solutional evolve to have steep walls overlooking their own breakdown debris (Fig. 3).

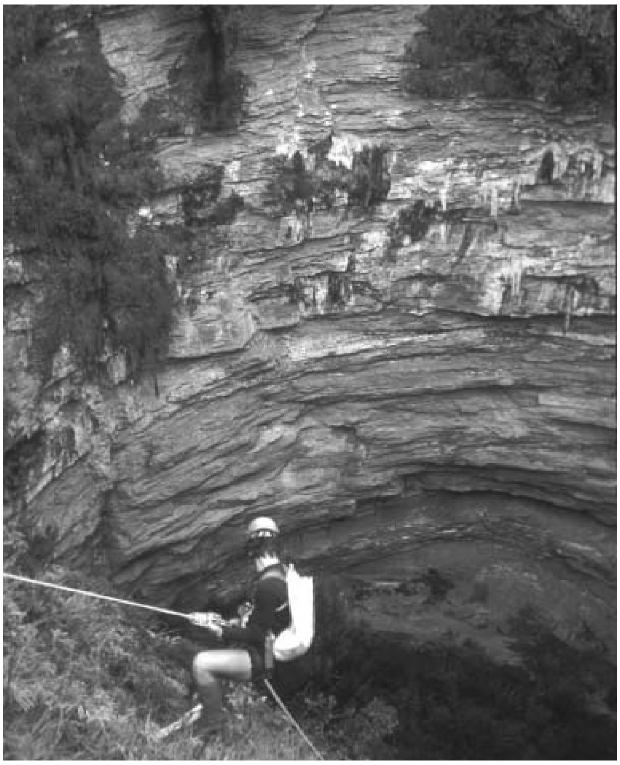

Fig. 3. A Rorogepo doline. (All photos by Alan Warild)

The floors of the Rorogepo giant dolines are covered with fine sediments, and some have ephemeral lakes, indicating that the conduits draining them are immature or blocked by sediment. The horizontal caves in them are small.

The Mamo dolines

The 100 km^2 plateau of Mamo has been called a doline karst (Francis et al, 1980a). It contains more than a hundred large dolines. One doline 600 m across has been seen from the air (Löffler, 1977), but it has not been found by field workers and is thought to be a very large solutional depression of unknown depth. Numerous rivers reach the northern edge of Mamo and then sink into the Darai

Limestone; without exception, the sinks are blocked by debris or sump. The resurgences of these rivers are believed to be 1000 m below the scarp on the southwest edge of Mamo (Fig. 4). These rivers possess sufficient aggressivity to create large caverns in the pure limestone beds of the Darai Limestone, beneath the siltstone cap of the Lai Formation that covers most of Mamo.

A few of the Mamo dolines have been explored around the Uliwapo clearing (James, 1974). The largest has a volume of 31M m^3 and also the dimension ratios necessary to be classed as a tiankeng (Zhu and Waltham, this volume). These are caprock dolines with steep, vertical and overhanging rock walls that require equipment for descent to their floors. In the largest dolines, there are no caves, but in the floor of one smaller doline of 3M m^3, a cave with a large stream is blocked by an unstable rockfall after 40 m of horizontal passage.

It is suggested that the Yu Rongoma is forming by solution voids in the limestone of a size suitable to create the giant dolines that are partially in the cover rocks. The river has a base flow of about 1 $m^3 s^{-1}$, and has much higher flows after heavy rain (James, 1974). However, even the high flows fail to remove the products of collapse as the voids stope upwards. The breakdown material from the siltstone and the Darai Limestone presents such an effective barrier that the river can no longer use its original route and out of necessity finds a new one. The new routes are immature, as input periodically exceeds reservoir capacity, and a lake forms at the Yu Rongoma sink in periods of continuous heavy rainfall (James, 1974). Such ponding further reduces the river's potential to remove the products of collapse by mechanical means. Each new route of the river beneath Mamo has the potential to form additional dolines; some lines of dolines have pronounced orientations, which are thought to be due to joint or fault control (Francis et al, 1980a).

There has been no further investigation of the most of the giant dolines on Mamo since the experiences of the 1973 expedition to the Muller Plateau led to an expectation that they would not contain caves. While the areas of the dolines can be accurately obtained from aerial photographs, their depths cannot, and caves are not always revealed. Some of the dolines have huge areas but it is thought that the depths of these are relatively small. Exceptionally high rainfall and tectonic activity in the region accelerate wall retreat. The result is that doline floors accumulate debris because there is no mechanism for removing the insoluble breakdown generated from the siltstone cap and the non-carbonate components of the Darai Limestone. It is possible that this vast array of caprock collapse dolines was formed by the rivers that now sink north of Mamo. It is likely that rivers in the past would have flowed further south and breached the 30-80 m of impermeable siltstone cap along faults and shear zones.

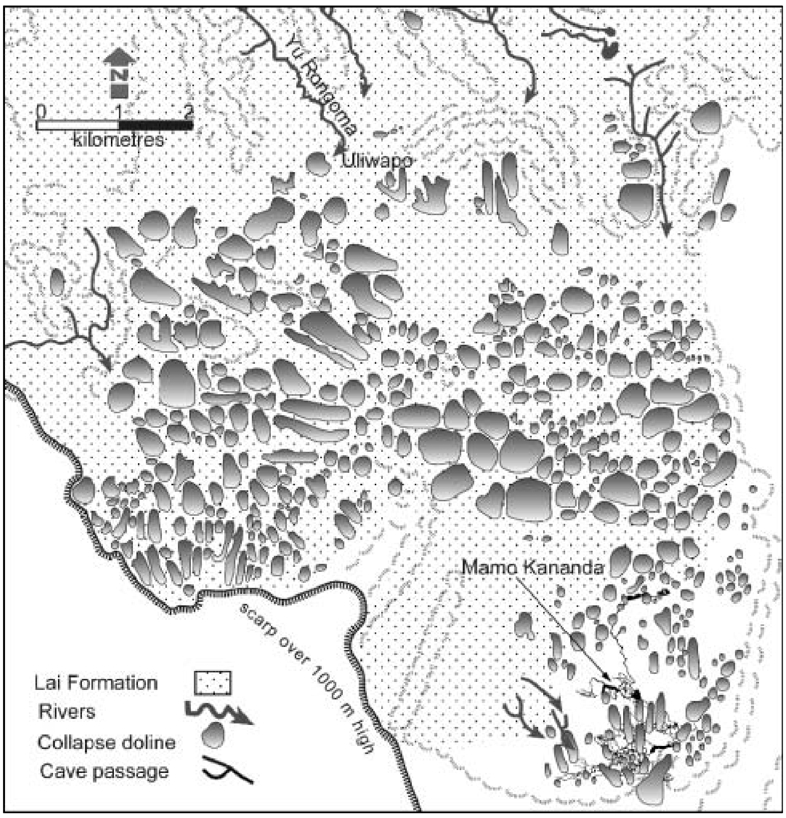

Fig. 4. The hundreds of dolines on Mamo. (Adapted from Montgomery, 1974)

In the southeastern section of Mamo, one circular doline has a volume close to 1M m^3 (Fig. 5). It has a nearly level rim in siltstone (Fig. 6), and a large cave entrance opens from its floor into Uli Malemuli. The cave and doline together reach a depth of 420 m. The caprock doline formed by collapse into a void that was originally part of the cave. Several small streams now gather on the surrounding siltstone and fall as glistening curtains into it. The upper beds of the Darai Limestone on Mamo produce dolines with vertical and overhanging walls, free from vegetation (Fig. 7). The pure limestone, friable siltstone and impure interbeds weather differentially: the limestone forms vertical faces, while the other beds crumble and retreat, forming overhangs above ledges covered with debris. Caves have formed in some pure limestone beds, and connect several dolines until terminated by wall collapse. The present silt and boulder floor often is 20 m below the most common level of the caves and may contain rock pinnacles between deep grikes. With the high denudation rates on the Muller Plateau, the limestone is rapidly eroded as soon as it is exposed.

Fig. 5. The Uli Malemuli doline

Where the Lai Formation has been stripped from the Darai Limestone in southeastern Mamo, a pyramid-and-doline karst has developed (James et al, 1980b). Here the dolines are much smaller than the caprock collapse dolines; they are formed by solution and are only slightly modified by collapse (Francis et al, 1980a). The 55 km of known passages in Mamo Kananda lie almost entirely beneath this pyramid-and-doline karst. The cave is characterized by extensive horizontal development at eight levels, each preferentially developed in the pure and more soluble limestone beds (James et al 1980b).

Fig. 6. The view out from Uli Malemuli into the doline.

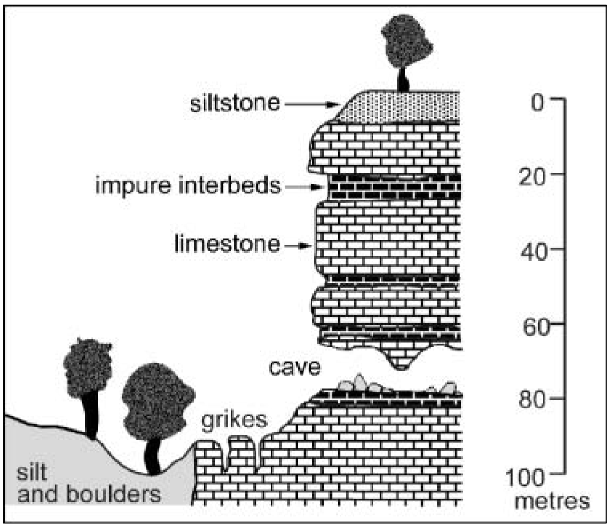

Fig. 7. Profile through the wall of a Mamo doline. (Adapted from James et al, 1980b)

Mamo Kananda has three chambers with more than 1M m^3 of air space, as evidence of the size of voids that can be generated beneath Mamo. The composition of the boulder piles on the chamber floors, and of the bedding exposed in the walls, shows that these chambers have formed by upward stoping through many beds of the Darai Limestone. The weak and friable impure limestone and clastic beds offer little resistance to the upward development, and the stoping is also assisted by cave passages in higher levels and by tectonic activity. The rivers that created the initial low-level voids no longer flow through the breakdown caverns in normal flow, but they invade the caverns in flood as their new routes to depth are immature or partially blocked. Space Oddity (Fig. 8) is a very large cavern at the lowest point reached in Mamo Kananda (525 m below the entrance). This is a classic dome chamber, but the walls show that even at this depth the Darai Limestone still contains impure and clastic beds, and its compacted floor debris demonstrate the impossibility of all but the largest rivers penetrating and removing the breakdown.

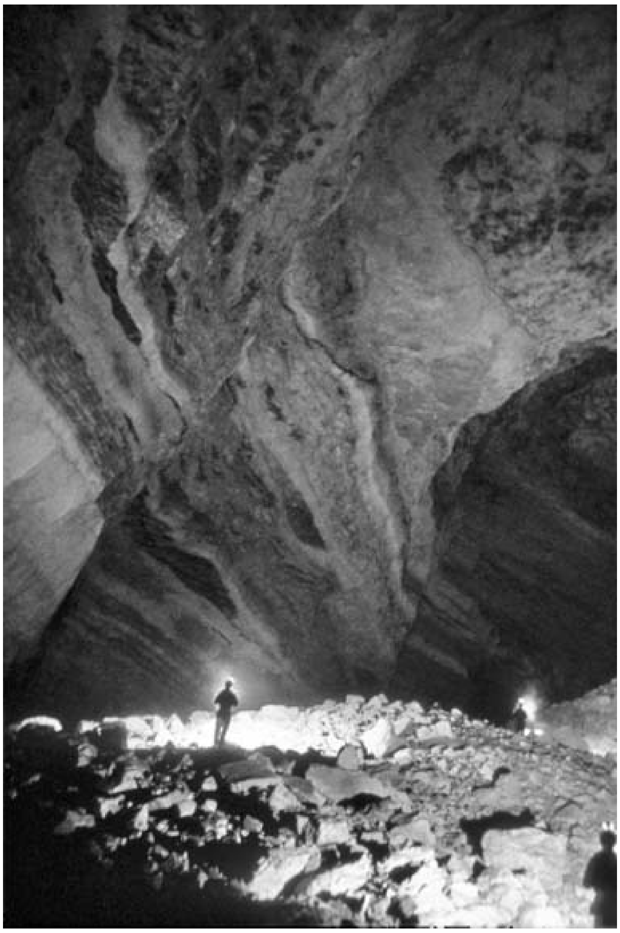

Fig. 8. Space Oddity, the terminal chamber in Mamo Kananda

If these collapse chambers in Mamo Kananda stope through to reach the surface, they will form giant dolines before they are further enlarged by wall retreat. However, the siltstone caprock has already been stripped above them, and rapid surface lowering is taking place mostly by solution. Even if the chambers are breached to create dolines, these are unlikely to reach the depths of the Nakanai megadolines or the Chinese tiankengs, as breakdown will continue to accumulate and floors will rise. They have only limited potential to become deeper if the rivers exploit new routes directly below the breakdown chambers and undermine the existing floors.

The Atea dolines

The Atea Doline is the focus of the Atea area (Fig. 9). It is where the Yu Atea sinks into the cave of Atea Kananda, with its 35 km of known passages. It is one of the most beautiful river sinks in the world (Fig. 10). The Atea Doline was first interpreted as a collapse feature because of the near vertical walls and the presence of collapse blocks on the floor (Caffyn 1974, James et al., 1976). However, it was formed when the Yu Atea breached the Lai Formation and invaded older passages formed by the much smaller Yu Dina (Fig. 9); it has therefore been classed as a solution doline (Francis et al, 1980b). In reality, it is neither of these, as it is a river sink at the end of a blind valley. More than 100 m in total depth and width, it compares in size to tiankengs and megadolines, but it has a stepped profile that lacks the diagnostic ring cliffs of a tiankeng and is open on one side (Fig. 11). The steep cliffs of the Atea Doline are a feature of basal sapping of pure limestone units lying over less permeable interbeds. Scars from recent rock falls are well developed on its southern wall.

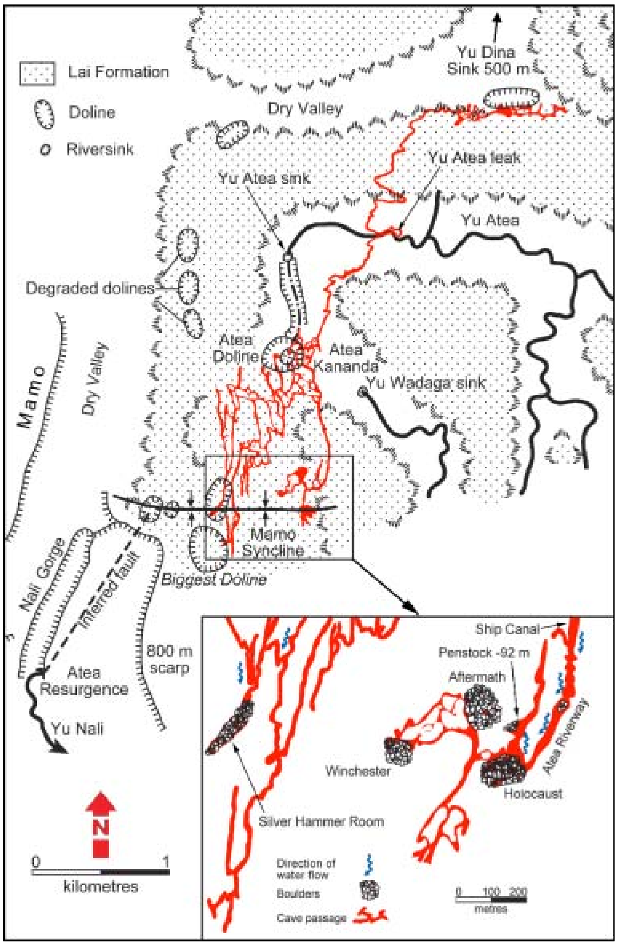

Fig. 9. Surface features in the Atea Doline area and their relationship to cave passages in Atea Kananda. (Adapted from Francis et al, 1980b)

Fig. 10. Aerial view of the Atea Doline

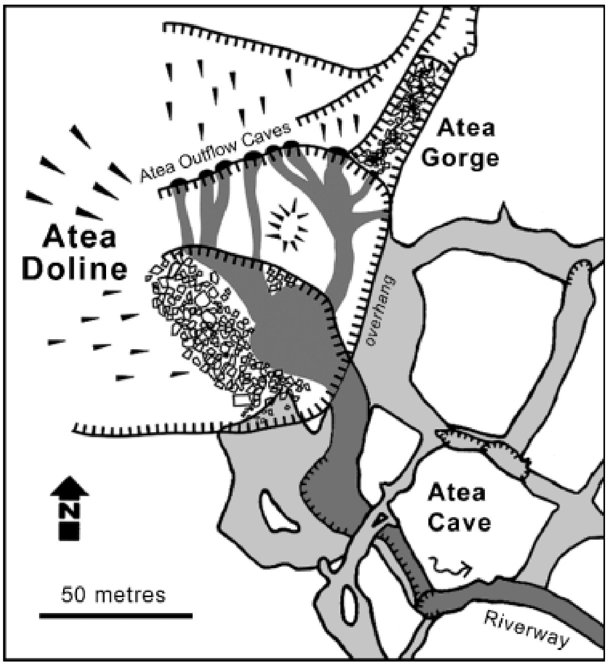

Fig. 11. Morphology of the Atea Doline. (Adapted from Montgomery et al., 1980)

The Yu Atea has flows and abrasive sediment loads both large enough to drive considerable mechanical erosion. The Darai Limestone interbeds provide fine quartz sand for this process, and the Yu Atea brings in additional quartz sand from the Ieru Formation (Gillieson, 1980). Chemical solution potential of the Yu Atea waters is also high, with the biomass of the tropical rain forests providing copious amounts of carbon dioxide to make its waters aggressive (James 1980). Despite this, the impure limestones and clastic beds in the upper Darai Limestone are resistant to solution; exposed surfaces develop insoluble clayey rinds after calcium carbonate is leached out. The insoluble residues also coat the pure limestone and inhibit its solution by the Yu Atea. This inhibition is so effective that the cave river carries (within experimental error) the same concentrations of dissolved calcium carbonate as it enters the Atea Kananda and as it leaves the Atea Resurgence (James 1980). This suggests that mechanical erosion dominates in the Yu Atea conduits, and is the major force for their enlargement.

The Yu Atea now sinks at the northern end of the Atea Gorge with the mostly abandoned gorge still taking flood flows (Fig. 9). The sinking waters resurge in the Atea Doline at the Atea Outflow Caves (Fig. 11) on top of a thick mudstone that forms a substantial ledge around the doline. The main flow of the Yu Atea emerges from the largest outflow cave, in which it rises from immature wall fissures beside a large collapse zone. This collapse has diverted some of the flow to form the other outflow caves, and the reduction in size of the main conduit forces the flood flows of the Yu Atea through the Atea Gorge. This is another example of the products of collapse of the upper Darai Limestone beds not being removed by rivers with very large flows.

On entering the Atea cave, the Atea river has cut chambers and shafts that drop 30 m to the Ship Canal, which is perched on a bed of mudstone 30 m thick. Flow slows in the canal, and insoluble residues coat the floor, walls and roof. The same materials have consolidated the breakdown in the Holocaust so effectively that the Yu Atea is forced back into one of its distributaries, where it now cuts down through the mudstone bed to sumps below the Penstock (Fig. 9). The large-scale collapses that have formed the breakdown chambers of Aftermath, Holocaust and Winchester, and also the Silver Hammer Room, all lie in the hinge zone of the Mamo Syncline (Fig 9), probably because the strike joints are there more closely spaced. As in Mamo, the breakdown piles are huge, and if their chambers stope through to the surface they will form giant dolines.

The Yu Dina is believed to have formed about half the known passages in Atea Kananda when it sank in the dry valley north of the Atea Doline and abandoned its surface course round to the west (Francis et al, 1980b). One of its courses south appears to have lain beneath the degraded dolines just west of the Atea Doline (Fig. 9). These dolines now have the bowl-shaped morphology of solution dolines, but have degraded from initial caprock dolines with steeper sides. Most of the Yu Dina passages are choked by sediment or collapse before they reach the Mamo Syncline. The far western passage ends in the Silver Hammer Room, a large breakdown chamber directly below a giant caprock doline on the axis of the Mamo Syncline. Despite being smaller than the Yu Atea, the Yu Dina was capable of forming a solution void large enough to initiate upward stoping, but it had insufficient erosive power to remove the breakdown debris and was forced to find a new route through the Mamo Syncline. Just south of the Silver Hammer Room and its overlying doline, another caprock doline near the Himbiraga dry valley, on the southern limb of the Mamo Syncline (Fig. 9), was once described as the biggest doline in the world (James, 1974). About 400 m long and 200 m across, it is well over 100 m deep, thereby matching the dimensions of tiankeng as defined by Zhu and Waltham (this volume); though its perimeter cliffs are broken and it has no river flowing through it.

The current sink of the Yu Dina is at the Dina Fault, where it can retreat no further upstream as it drains off the non-carbonates of the Ieru Formation (Fig. 12). Its postulated route to the Nali is too deep in the limestone for its caverns to stope upwards to reach the surface; great depth below the surface accounts for the large collapse chambers in Muruk Cave not forming new megadolines in the Nakanai Mountains (Audra, 2001).

The Yu Atea is already forming a new sink at Yu Atea Leak (Fig. 9) as the siltstone cap is removed from limestone that contains an existing stream cave. Evidence from Rorogepo and Mamo indicates that the number of potential stream and seepage sinks increase when the Darai Limestone is exposed. The result is that the underground conduits fragment, and dolines created by collapse or solution are smaller. Hence, as the Yu Atea retreats headward it is unlikely to develop giant dolines. Downstream of its known cave, the course of the Yu Atea appears to lie so deep below the surface, and with such a steep gradient, that future development of giant dolines is again unlikely.

The Muller giant dolines in context

The giant dolines are the largest karst features on the Muller Plateau, as are the megadolines in the Nakanai Mountains and the tiankengs in South China. In common with the other two areas, they have formed after rapid uplift in places where there is continuing tectonic activity. China's tiankengs are thought to have been formed mainly formed in the late Pleistocene (Zhu and Chen, this volume). Consideration of both mechanical and solution erosion rates, and the chalky nature of the host limestone also place Nakanai's megadolines in the late Pleistocene (Audra et al, 2001). Opinions are that the Muller Plateau was established in its present form about a million years ago (Francis et al, 1980a), and this means that the Muller dolines have also developed during the Pleistocene. However, it is impossible to place them more accurately within this time frame, as it is believed that some will have been formed sequentially by the same underground rivers.

Classification of dolines on the Muller Plateau is complicated because the solution and collapse dolines have very similar appearance. It is also understood that no giant doline is entirely formed by collapse or solution; the name merely implies that one process dominates. Despite this, it is possible to be confident that all the giant dolines of Mamo and Atea are caprock dolines. The Nakanai megadolines and the Chinese tiankengs are largely collapse dolines, with a proportion of caprock dolines. The Muller Plateau dolines are distinguished by lying high above the active cave rivers, and the Mamo sector is remarkable for its high density of giant dolines.

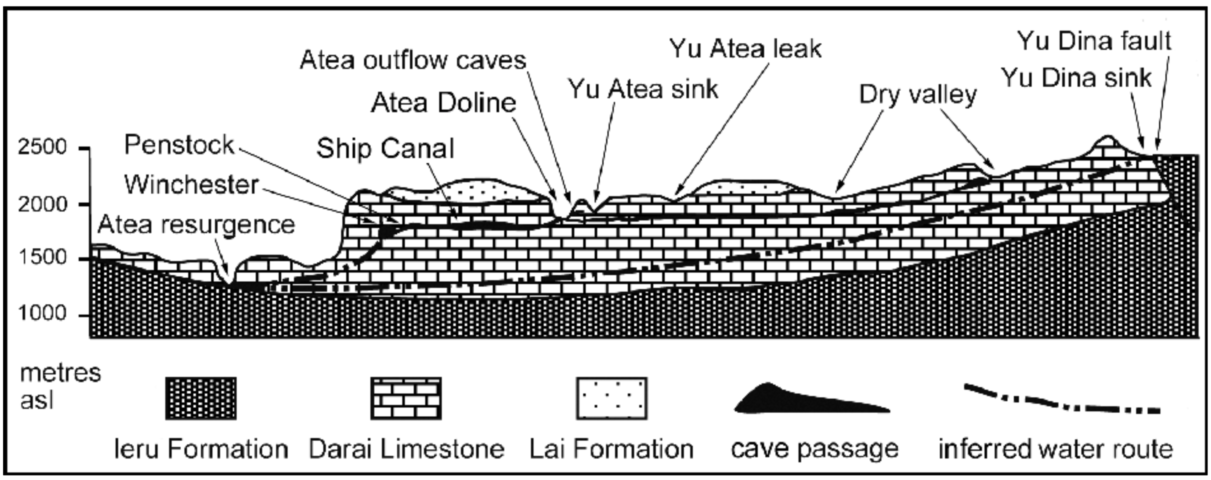

Fig. 12. Profile through the Muller Plateau in the Atea area. (Adapted from Francis et al, 1980b)

The relative amounts of mechanical erosion in the three regions depend on river size and abrasive load; South China may well rank first in both of these. In terms of the limestone geology and its ability to support mature karst, the Muller Plateau is formed on the impure sequences of the Darai Limestone that appear to have properties in between those of the ancient, hard, compact and pure carbonates of South China and the friable and porous Yalam Limestone of the Nakanai. The purity of the limestone is directly related to its solubility, and the Darai Limestone has numerous interbeds that resist solution. In South China and the Nakanai Mountains, chemical corrosion enhances mechanical erosion. In contrast, on the Muller Plateau chemical corrosion is limited, and in many cases not available, for removal of collapse material.

The quality of the rock also affects the scale of karst features. Although many of the common karst landforms are found both on the Muller and in the Nakanai, they are poorly developed and are generally covered in vegetation. Young, weak and porous limestones may not be expected to support large karst features (Yuan et al. 1998). It is therefore surprising that the giant dolines are found both in the Nakanai and on the Muller Plateau. Their development on the Muller Plateau could have been aided by the presence of a caprock. Perhaps, the veneer of volcano-sedimentary deposits on the Yalam limestones on the Nakanai has had a greater role in the development of the megadolines than simply channeling runoff into the conduits to feed their enormous rivers. These are the rivers, which transform the megadolines from just depressions filled with tropical forest into magnificent and awesome sites.

The tiankengs of South China, with their vertical cliffs of bare rock are without doubt among the largest, most impressive and aesthetically pleasing karst landforms in the world. The giant dolines of the Nakanai and the Muller stand close behind them, and are equally remarkable as features of geomorphological significance.

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