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Burial and infilling of a karst in Papua New Guinea by road erosion sediments

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Abstract The anthropogenic impact on karst in Papua New Guinea is briefly introduced and a specific case is presented detailing the effect of road erosion sediments on a small karst. The karst is in the perennially humid tropics and covered with primary rain forest. The road was placed high above the karst on steep friable rock and traverses several of its catchments. The changes to and the rate of burial of parts of the karst and the infilling of the caves are described. The karst drainage has altered, and there is increased water storage. The sediment build-up ceased in less than a year due to vegetation and stabilization of the road embankments. It is concluded that any construction within a catchment leading to a karst should be assessed as to its impact on the karst.

Key words Road erosion sediments—Perennially humid tropics—Karst cave systems

Introduction

Karst comprises some 20 percent of the area of Papua New Guinea (PNG). Much of the country is mountainous and is a tectonically active zone where earthquakes are frequent and often intense. The highland and southern karsts are located in the perennially humid tropics and covered with primary rain forest. This combination of relief, prolific vegetation, and a climate characterized by constant high temperatures, a high humidity and rainfall, often falling during exceptional storms, is ideal for both physical and chemical geomorphic processes. It is not surprising that the denudation rates quoted for PNG are some of the highest in the world and that many mass movements of rock and soil occur even in uninhabited areas (Löffler 1977; Jackson 1984). Superimpose an anthropogenic impact upon these intense natural geomorphic processes, and the results can be catastrophic. The valleys of the Central Highlands of Papua New Guinea support large populations where for the last 1000 years there has been a steady increase in horticulture, which has slowly resulted in deforestation, nutrient depletion, and land degradation (Gillieson and others 1986, 1987). In some karst areas the degradation is widespread; for example, in the Chimbu Gorge, where slash-and-burn methods are used to cultivate slopes of 45°, soil stripping has resulted in bare limestone slabs and filled dolines. In the past 50 years the anthropogenic impact on a number of karsts has been further increased by the construction of roads through them and the subsequent movement of the population and their gardens towards the highways.

The primary-forest-covered mountainous karsts of PNG that were once the sole domain of nomadic hunter–gatherers are now being intensively explored by oil and mineral prospecting companies. The exploration camps and drilling sites are usually established by helicopter and do little permanent damage to the karst. However, the subsequent mining operations and their associated infrastructure can have considerable impact, as this paper illustrates.

The first major mine to be established on the Papua New Guinea mainland was at Mount Fubilan (Fig. 1), a porphryitic diorite/monzonite intrusion containing substantial amounts of gold and copper. Ok Tedi Mining Limited (OTML) is mining the mountain, and the mine has both infrastructure and roads on karst. Prior to the development of the mine, baseline environmental data were gathered by potential miners and the PNG government (Jackson 1984). Throughout the construction stages and mining, OTML has supported a comprehensive environmental program to assess and control impact of the mine on the Ok Tedi catchment, the Fly River, and the Gulf of Papua.

The disposal of tailings was one of the major challenges presented by the mining of the Mount Fubilan. The first disposal site, on the Ok Ma some 4 km above Lukwi, was abandoned when a partially constructed dam was

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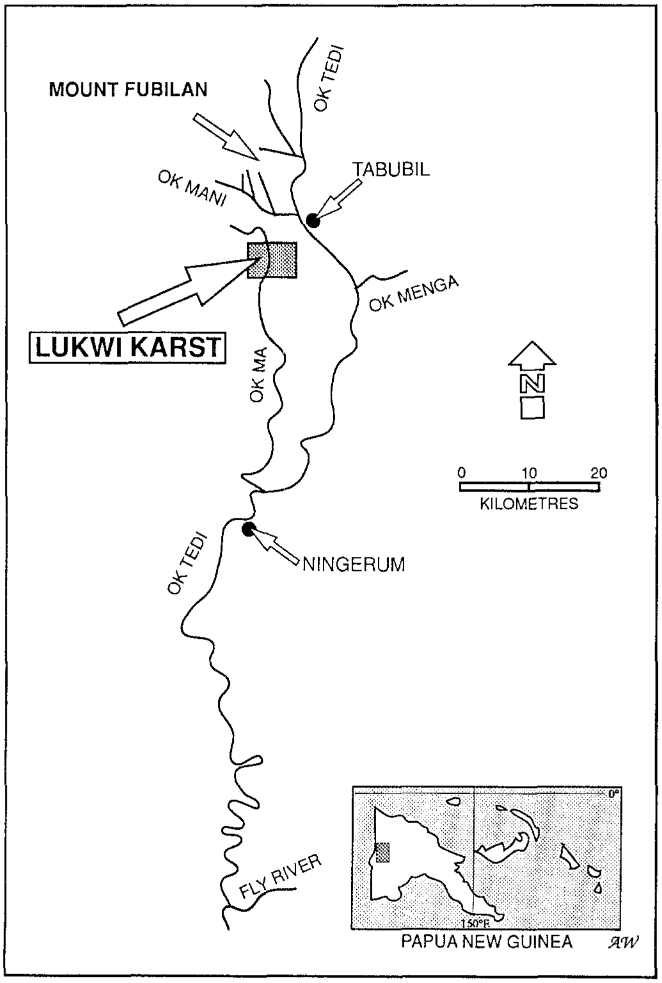

Fig. 1. Location map

destroyed by a landslip and floods. In 1984, Lukwi was one of several sites being considered for a new tailings dam and pond. It was the only site with an extensive area of outcropping limestone. The suitability of Lukwi for tailings disposal depended upon the extent of karstification of the limestone; therefore late in 1984, seismic and drilling investigations were undertaken. In addition, OTML was advised that a speleological study at Lukwi would be beneficial. There had been two earlier speleological investigations of karst in PNG: the Waga hydroelectric scheme (Jacobson and Bourke 1975) and the Ok Menga hydroelectric scheme (Pound 1977). A speleological investigation of Lukwi was commissioned and, based on its preliminary results (James and others 1985a), Lukwi was designated as the new tailings disposal site. Further speleological investigations were made to assist the consultant engineers with the location of the dam center line, the coffer dam, the diversion tunnel, and the position and extent of the grout curtains (James and others 1985b). The entire Lukwi karst was to be covered by the dam structure and the ponded tailings; therefore, every effort was made to document the karst completely in order to provide baseline data for an assessment of the changes to it caused by burial under tonnes of tailings, should the Lukwi karst re-emerge in the future.

The Lukwi karst

The Lukwi karst lies on both banks of the Ok Ma between its junction with the Ok Mi in the north and the Ok Dui in the south (Fig. 2). It is developed in three distinct Neogene stratigraphic units, the Era beds, the Orubadi beds, and the Pnyang Formation (Fig. 3) Two limestone units in the Orubadi beds and the Warre Limestone member of the Pnyang Formation have developed surface karst features and are cavernous. The Orubadi beds are about 20 m thick and are mainly fine-grained, grey–green interbeds of calcareous mudstone and argillaceous limestone (James and others 1985a). The Warre Limestone is 65–85 m thick throughout the area and is a creamy white, friable-to-firm micritic and detrital limestone dipping in a northeasterly direction, with dips rarely exceeding 10°. Overlying the limestones and forming the local ridge tops are the Era beds: grey, friable, firm impervious volcanoclastic mudstones, siltstones, and sandstones.

The karst surface on the Warre Limestone has an area of 5 km^2, almost equally divided between the east and west banks of the Ok Ma. On both sides of the river it forms terraces 250 m wide and fringed by 30- to 40-m-high cliffs (Fig. 2). On the terraces are areas of solution dolines, of dolines and corridors, and extensive regions of crevice karst. The east bank crevice karst shown in Fig. 2 has a high fracture frequency, controlled by 40° and 120° jointing. Depth of the crevices is highly variable, the deepest (40 m) being close to the cliffs or where there is a streamsink. Throughout the karst there are gorges, canyons, and dry blind or semiblind valleys that have been developed by surface stream flow despite the permeability and solubility of the limestone. The principal karst feature of this type is the canyon of the Ok Ma itself. The river arrives at the edge of the limestone with a considerable volume of flow (average discharge approximately 19 cubic metres per second; Klohn Leonoff 1984) and does not appear to lose any of this into its bed. The Lukwi karst contains 25 known caves that together have 7.0 km of mapped passages. The major caves are shown in silhouette in Fig. 2. A complete description of the caves at Lukwi is contained in James and others. (1989). Lukwi is a mature open karst with karstification extending on the west bank to a base level that lies below the sediment-perched channel of the Ok Ma. The east bank karst is perched 5 m above the Ok Ma on impure limestone beds.

The traditional uses of Lukwi were hunting, gathering, and cultivation of a few small stands of sago palms. Harvesting of sago causes little damage to the karst because only the stems about to flower are removed and the plants take 8–15 years to mature (Powell 1976). The valley is covered with typical premontane tropical rain forest containing some magnificent trees with trunks up to 1 m in diameter and 30–40 m high. The forest has a luxuriant canopy and a moderate understorey; its composition and density is similar on and off the karst.

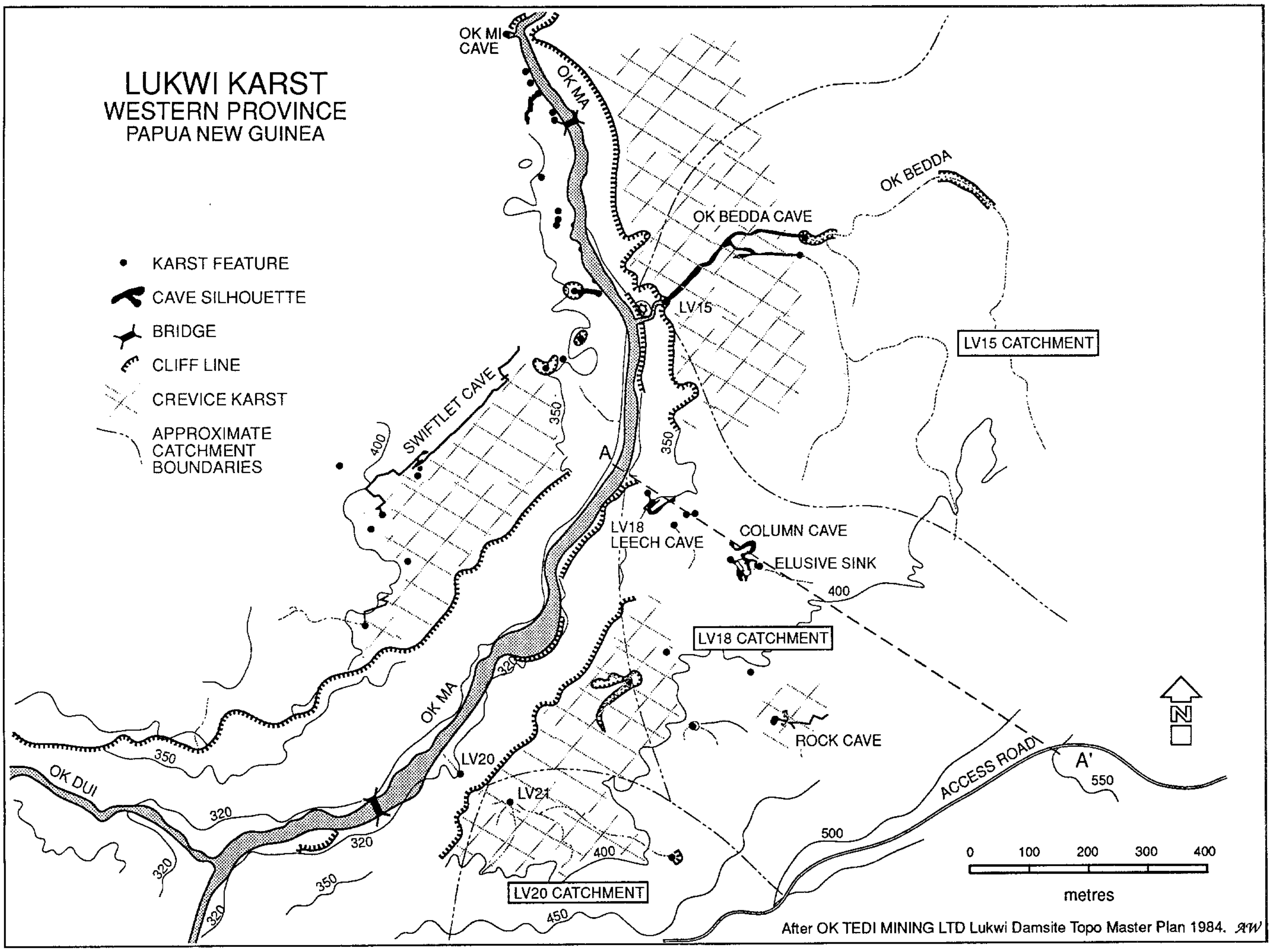

Fig. 2. Map of the Lukwi karst, Papua New Guinea

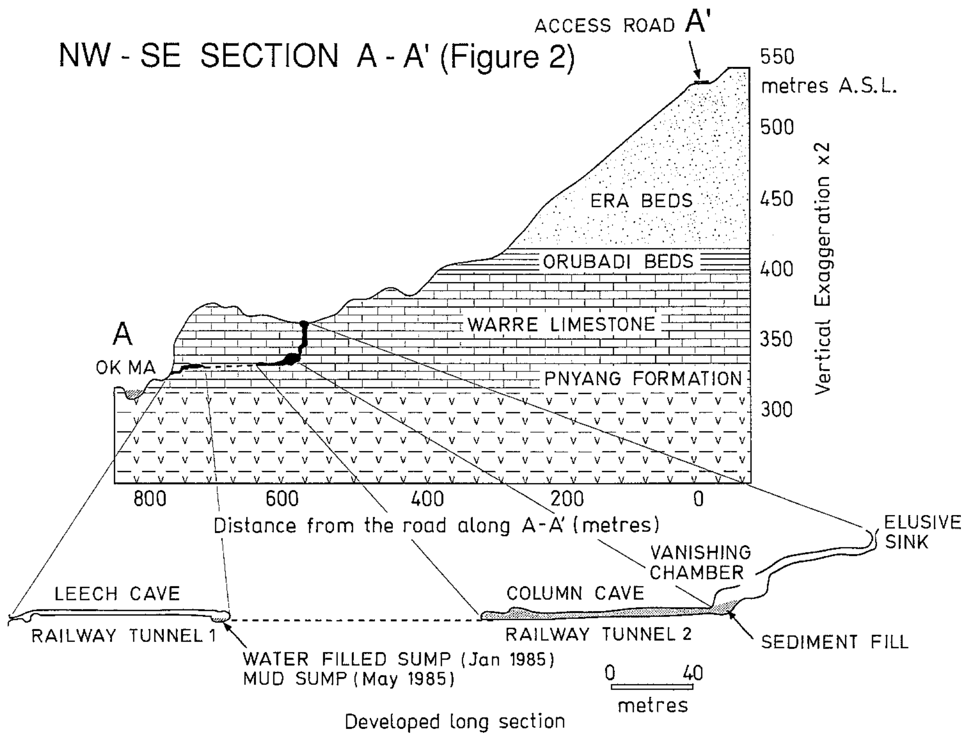

Fig. 3. Cross section of the east bank of the Lukwi karst, along A–A′ of Fig. 2

Fig. 4. Erosion of the Lukwi road embankment, May 1985

In late 1984, a road was constructed along the east ridge above the Ok Ma karst to provide access for geotechnical equipment. In January, May, and July 1985 during the speleological investigations it was possible to record the changes to the Lukwi karst geomorphology and hydrology caused by a massive invasion of road erosion sediments. There was no road on the west ridge of the Ok Ma valley, so comparisons could be made between the altered east and unaltered west bank situations.

The access road (Fig. 3) was placed high on the easily excavated Era beds by clearing a wide track of primary forest. The road was bulldozed in, either on or just below the crest of the ridge, with no effort being made to move or consolidate the excavated vegetation, soil, and rock. The road was not sealed and its surface was finished with crushed limestone; immediately after construction, runoff began to cause considerable erosion of the roadway and its embankments. Figure 4 shows the degree of erosion of the road embankments in May 1985. In July there was considerable growth of natural vegetation on the embankments and some enterprising Papua New Guineans had already assisted their consolidation by planting vegetable gardens.

In 1984, the precipitation measured at Lukwi was 8300 mm (R. Wallwork, personal communication). The Lukwi climate falls into a premontane perhumid classification and evapotranspiration is expected to lie in the range of 1400–1800 mm (McAlpine and others 1983). This gives an estimated mean annual water surplus of some 6000 mm. The result is that the runoff from the impervious Era beds on to the karst is immense. The road traverses along the crests of three of the east bank catchments (Fig. 2), which drain to three major karst springs: LV15 (the Ok Bedda Cave entrance), LV18 (Leech Cave entrance), and LV20 (a spring that is blocked by debris). Table 1 provides catchment data for the three springs and gives the length of the road in each catchment. The east bank catchment areas were calculated from water tracing results, the speleological investigations, and the topography (James and others 1985b).

Table 1. Changes to the karst surface, caves and drainage

Catchment	~ area (km^2) (% on karst)	~ road length (km)
LV 15 (Ok Bedda Cave)	1.5 (25)	1.2
LV 18 (Leech Cave)	0.4 (35)	0.5
LV 20 (LV 20)	0.2 (60)	0.5

Sediments eroded from the road were washed 150 m vertically down the steep impervious surface of the Era beds, across or through the Orubadi beds, and onto the Warre Limestone terraces. The first evident results included considerable alteration to the karst surface topography and drainage in the LV20 and the LV15 catchments (see Fig. 2). In January 1985 (some three months after the road was completed), a blind valley containing streamsink LV21 in the LV20 catchment had become a desert within the lush forest; it was infilled with sediments of unknown depth, with the stream sinking through them in a collapse doline where LV21 had been. The crevice karst to the east of it was partially filled, the filling converting what had previously been a very difficult area to negotiate on foot into an easy walk along silt-floored corridors, some of which terminated abruptly in rock walls at the base of which small streams sank into silt. Blocks of limestone in one area were isolated by the sediments to create a stone forest with pinnacles 10 m high. When the area was re-examined in May 1985 further sediments had filled the LV21 blind valley completely; the stream could no longer sink but flowed at the surface instead, to fall over the river cliffs as a waterfall. In July 1985 the sediment pan in the blind valley had a dense low cover of vegetation.

In the LV15 catchment, a broad blind valley leading to

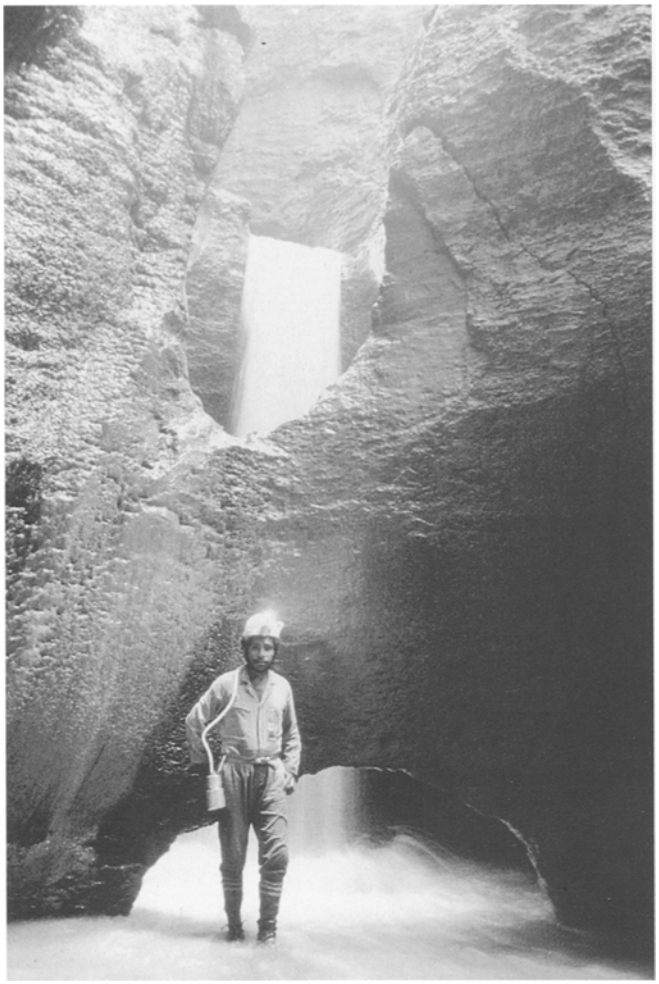

Fig. 5. The waterfall entrance to Ok Bedda Cave. Sediments eroded from the Lukwi road were cleared efficiently through this steep section

Ok Bedda Cave displayed sediments about 0.5 m deep in January 1985. They spread across the entire floor, partially burying the vegetation. It appears that the Ok Bedda streamsink had become blocked temporarily, causing the valley to flood. Higher in the catchment some of the karst features on the Orubadi beds had survived burial; for example, only the floor in the small gorge shown in Fig. 2 was covered with road erosion sediments. In May 1985 no extra sediment had accumulated in the Ok Bedda blind valley and stabilization of the previously deposited sediment by vegetation had commenced.

There were only minor surficial manifestations of the influx of sediments from the road in the LV18 catchment during the six-month period. Creek beds on the Era beds and Orubadi were scoured, littered with a few cobbles, and vegetation on their banks was destroyed. Some karst features of the Orubadi beds were modified by filling. On the Era beds subsidence dolines caused by cavities in the Orubadi limestones were now sediment-filled.

In Ok Bedda Cave, road erosion sediments, logs, and other vegetal debris were spread throughout the large, horizontal trunk passage. Depth of the sediments varied daily; during the hours of low flow they built up, and when the rains brought high flow, they were removed again. The depth of the plunge pool of a 5-m waterfall at the sink (Fig. 5) varied from 1.5 m to 0.25 m. In contrast, a tributary passage of Ok Bedda Cave that drains a small catchment isolated from any road sediment influx had clean-washed scalloped walls and remained completely free of sediment. During a dry period in May 1985, a fan of sediment could be observed extending 5 m out into, 10 m up, and 20 m down the Ok Ma at its junction with the Ok Bedda creek.

Caves in the LV 18 catchment were also affected . In January 1985, the Elusive–Column–Leech Cave system (Fig. 3) was infilled between Column Cave and Leech Cave by road sediments. These had entered the system through

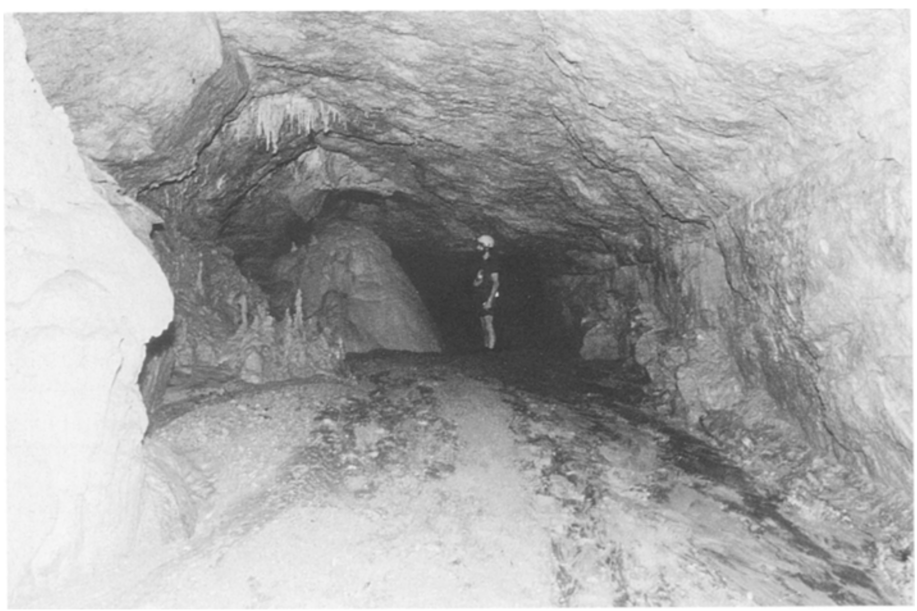

Fig. 6. The horizontal passage, Railway Tunnel 2, Column Cave, in January 1985 when it was beginning to fill with debris from the Lukwi road. It had filled completely before the end of May that year

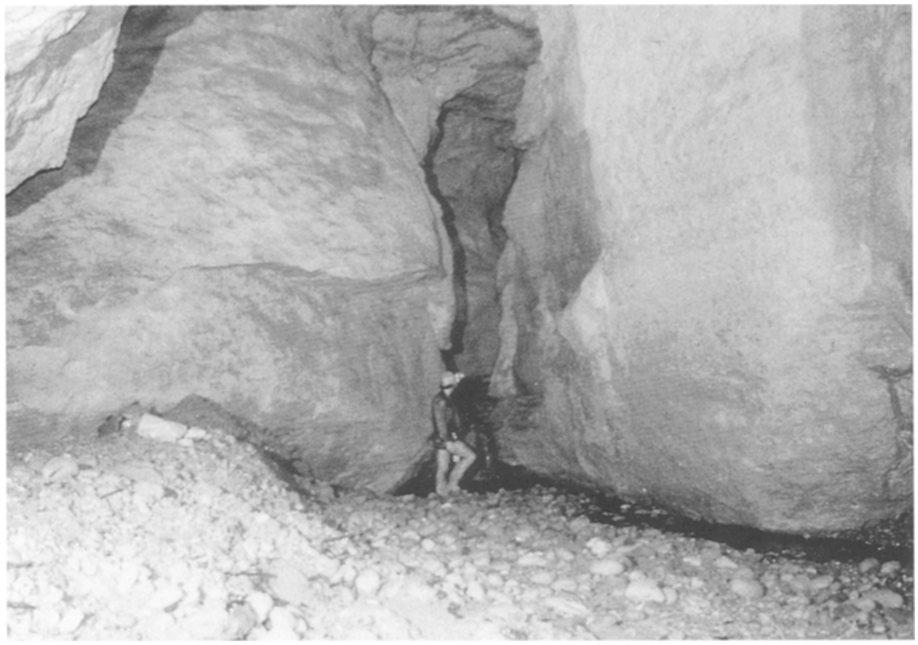

Fig. 7. Road fill in Vanishing Chamber, Column Cave, May 1985. The large cobble debris includes limestone clasts from the roadbed

Elusive Sink, leaving only discrete evidence of their passage through the cave until the end of a large gallery known as Railway Tunnel 2. This was abruptly terminated by a sediment blockage (Fig. 6). In May, the entire Railway Tunnel 2 was filled with the sediments to within 0.5 m of the roof and several meters of sediment had accumulated upstream in Vanishing Chamber. On top of the sediment bank were large cobbles from the Era beds and limestone from the road surface (Fig. 7). One week later Railway Tunnel 2 was filled to the roof. Where older phreatic sections of Column Cave intersected the modern vadose drainage, there were new sumps (water traps) and the passages showed evidence of backflooding. When Column Cave was reexamined in July there was no significant increase in the depth of sediment.

Caves in the LV20 catchment were smaller. Their passages terminated in sediment blockages in January. By May they were completely buried and there was no flow from the spring LV20.

Discussion

In the period between January and July 1985, the karst and caves on the west bank of the Ok Ma remained free of sediment, unusually so, because in general, the karst and caves of PNG are exceptionally muddy. The caves stayed sediment-free even when the primary forest in their catchment had been felled but not cleared. Constant flushing by the daily rain keeps the west bank caves clear of the sediment generated by most natural processes. It was the excavation for the road in friable rock and the failure to remove or stabilize road surface, embankments, and spoil that produced the vast amount of sediment trapped by the east bank Lukwi karst.

Sediments eroded from the road were transported to the karst by overland runoff and channel flow during frequent intense storms. No movement of the sediment was observed during light or misting rain. There were no barriers to the progress of the sediment-laden waters across the steep impervious Era beds; therefore, streams ran on to the limestone with high velocities and carrying substantial quantities of sediment in suspension and as bedload. Where, on reaching the limestone, the waters followed a shallow course, usually along blind valleys, they lost carrying capacity gradually and deposited their sediment load progressively. Where they sank directly into shafts, most sediments were carried through into the horizontal cave passages beyond.

Before the construction of the road, the drainage system of the east bank Lukwi karst would have been one with large turbulent flows under gravity passing through caves to springs. At that time, the karst would have had negligible water-storage capacity. The Ok Bedda Cave retained these characteristics throughout the period of sediment invasion despite having the greatest length of the road in its catchment (Table 1). This can be attributed to its possessing a comparatively straight, direct route between the sink and the spring, to the uninterrupted large dimensions of its principal passages and to the frequent occurrence of large discharges (more than two cu. meters per second). Such discharges, when confined within a cave passage, are expected to maintain excellent scouring capacity, and this was confirmed by the continuous clearance of sediments through this cave.

The Elusive–Column–Leech Cave system drains a smaller catchment with a shorter section of road than does Ok Bedda Cave; its discharge is about one quarter the size. The water inputs to this system are dispersed between at least ten shafts and dolines (James and others 1985b). In this cave system there are some passages that are larger than those in Ok Bedda Cave, but they are part of a complicated labyrinth of vadose and phreatic passages that meander en route to the spring. The early blockage of this cave system and its consequent rapid filling suggests that there were one or more crucial constrictions caused either by a reduction in the original passage size or by the presence of flowstone barriers—Column Cave is the best decorated cave on the east bank and contains a number of large calcite flowstones (Fig. 6). An alternative or additional explanation of the blockage is that the waters, in their meandering route down the horizontal Railway Tunnel, lost much velocity and thus deposited their sediment load, back-filling the passage. The waters were compelled to follow new routes, and in places vadose flow changed to epiphreatic flow. Flow-through times between sink points and the spring were increased considerably and several temporary water storages were created.

The LV20 spring has the least flow of the three major springs, and the caves explored in its catchment had constricted entrances and passages. Early blockage resulted in complete loss of the underground drainage and the burial of a large area of karst.

Calculations from cave survey data show that at least 2400 m^3 of sediments eroded from the road were deposited in Column Cave during a four-month period. This was from a cleared area on the Era beds that was less than 0.03 km. If these figures are converted to a denudation rate, they eclipse any natural process. That there is vigorous natural erosion at Lukwi is demonstrated by the turbidity of streams in the rain forest during intense storms and the ever grey and opaque waters of the Ok Ma. Before mining commenced at Mount Fubilan, it was estimated from the sediment load and discharge of the Ok Tedi that more than 30 mm of soil and rock were being removed per year over the entire 420 km^2 Ok Tedi catchment (Jackson 1984). The detritus produced by natural processes can be transported through the karst more easily than the road erosion sediments because it has been broken down into much smaller grain sizes by chemical processes in the forest soils. The supply of coarse, clogging sediments in the karst decreased abruptly when most of the material excavated for the road had been eroded and the remainder became stabilized by settling and regrowth of vegetation. The road and its surroundings will continue to supply abnormal amounts of sediment to the karst for many years because of the removal of the forest. Studies of the age structure of primary forest in PNG show that there is an approximately 50-year cycle in forest replacement (White cited in Löffler 1977). Once the sediment supply to the karst decreased, vegetation was able to stabilize the surface. Sediment stabilized in this manner will be removed only slowly from the karst. We cannot predict if it will be removed from the smaller caves, but the large, vadose passage of Ok Bedda Cave was washed clean again by February 1987 (Robin Ette, personal communication). The Column Cave system has not been visited since 1985, but it had the potential to reach a steady state where sediment input equaled output or to slowly accumulate sediment. In addition, in this cave, the sediment may be immobilized beneath calcite flowstones.

The invasion of the karst by the sediments restricted our speleological investigations, particularly in the region of the proposed dam center line where it prevented a full exploration of the Elusive–Column–Leech Cave system and a detailed examination of crevice karst to the east of LV21. In preparation of a karst site for a dam, all unconsolidated materials must be removed before construction or grouting can take place because they are likely to shift under hydraulic pressure (Milanovic 1981). At Lukwi a comparatively clean karst was converted into a very dirty one by careless road construction. The only feasible way to remove the trapped sediment will be to remove the karst.

Burial of the karst and infilling of the caves could have been prevented by removing or stabilizing the excavated material. An alternative would have been to place the road on the limestone. However, a number of unfortunate incidents have occurred in PNG when roads have been placed on karst. For example, during the construction of the Mount Fubilan mine haul road, a bulldozer disappeared into an enormous cavern that subsequently took four days to fill (Ross Hastings, personal communication).

Conclusions

The changes to the Lukwi karst were a direct result of road construction in its catchment. The burial of the karst surface hid its true nature and created an unstable surface. Sediment blockages in the caves caused underground drainage to become surface drainage, caused flooding, and caused springs to dry up. At Lukwi none of these events presented any hazard to people; however, in inhabited karsts, there would have been inconvenience and damage at the least. This case study, despite being from one of the wettest karsts in the world has wider significance—the transport of the sediments took place only during intense storms, which can occur almost anywhere, even in deserts. In this study it was the construction of a road in the catchment that radically changed the karst both above and below ground. In general, however, any type of construction in or alteration to a karst catchment should be assessed for its potential impact on the karst.

To date the Lukwi Tailings Dam has not been built. Alternative ways have been found to dispose of the tailings so that the long-term experiment involving the complete burial of Lukwi will not take place. Instead, a similar but more environmentally acceptable study of the burial of a small section of the Lukwi karst has been possible, and there can be further studies to monitor the rate at which the karst is restored and assess any damage to it within a reasonable time frame.

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