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Julia M. James

Moai, Easter Island

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Cover: One of the many moais gazing out to sea on Easter Island.

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The Effects of Fire on Soluble Rock Landscapes

. . . . . Ernst Holland

Abstract

The spalling of limestone as a result of fire is discussed. Numerous observations throughout Australian karsts show that the effects of fire on limestone vary with its type, the intensity of the fire and the nature of the limestone weathering. An associated laboratory study of the effects of heat on limestone is also discussed.

Introduction

The effects of Australian bush fires have been examined in detail in relation to fauna, flora and erosion, however studies of their effect on bedrock are sparse. Selkirk and Adamson (1981) documented the effect of fire on Sydney sandstone and the flaking of the rock making the observation that fire is an important agent in sculpting the land surface. This paper presents a study of the effects of fire on Australian karst. Naturally ignited bush fires, devegetation (agriculture) and regeneration (forestry) burning and fire hazard reduction burning have occurred in Australian karst areas. Observations after such fires have enabled a number of general conclusions to be reached as to the effects of fire on karst. These general conclusions are complemented by an associated laboratory study of the effect of heat on limestone.

Bedrock Break-up -Spalling

The direct effect of a fire on limestone is the removal of the rock surface as shards resulting in the destruction of karren (minor solution features) and producing a colluvium of shards. Fire reduces limestone to shards so effectively that it has been used throughout history for shattering limestone; it is still used today by the residents at Jenolan Caves, NSW to remove limestone outcrops from their gardens. Excavation of soil at the bottom of small limestone cliffs in the nearby McKeowns Valley revealed identical material (Figure 1).

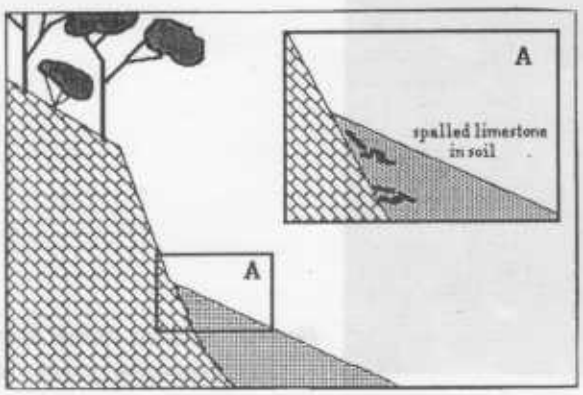

Figure 1. Spalled material at the foot of slope, Jenolan Caves.

Spalling in common with larger-scale exfoliation can be due to a variety of physical and chemical processes. Jennings et al. 1982 recorded the incidence of spalling on a number of Australian limestones relating its occurrence to the degree of metamorphism of the rock. They proposed a number of mechanisms by which the process could occur but failed to postulate fire as a possible cause.

Frost shattering reduces limestone to a colluvium of shards, a feature of all alpine karsts. Thus, the shards produced by cold climate processes, both past and present, may be difficult to distinguish from those generated by heat. The resulting frost shattered and fire spalled landscapes are similar. Marques (1990) also observed that environmental modification derived from fire devegetation gave rise to periglacial-type features.

Spalling directly attributable to fire has been recognised on four Australian limestone groups (Figure 2):

- Precambrian and Cambrian limestones of the Carpenteria basin of northern Australia
- Ordovician, Devonian and Silurian limestones of eastern Australia
- Miocene limestones of the Eucla Basin southern Australia
- Quaternary aeolian calcarenites of southwestern Western Australia and southeastern South Australia

The size and morphology of shards produced vary with rock type but modifications to the landscape are similar.

Spalling as a result of fire has been recorded on non carbonate rocks (Emery 1944; Selkirk and Adamson 1981; McNickle 1985). On such rocks spalling is known to occur from a variety of physical and chemical processes (Jennings et al. 1982). A feature unique to carbonate rocks is that at high temperatures they "calcine", a process which totally disintegrates the rock.

$$CaCO_3(s) \xrightarrow{heat} CaO(g) + CO_2(g)$$

calcium carbonate → calcium oxide + carbon dioxide

The dissociation temperature for pure calcite is 898°C and always proceeds gradually from the external surface inward (Boynton 1980). The chemical breakdown may occur at lower temperatures, for example, Azbe (1939) has detected traces of surface dissociation with temperature as low as 742°C for rocks with a high calcium content. These temperatures are well below those recorded for the hottest vegetation fires.

The extent of a fire spalled material has been used to establish the boundaries of past fires, for example, on the Nullarbor Plain, WA the Miocene limestone is generally exposed around the edges of dolines, as karst pavements or due to root heave around trees and bushes. The limestones that have been subjected to fire exhibit a blocky spalling and the oolitic nodules of calcrete in the

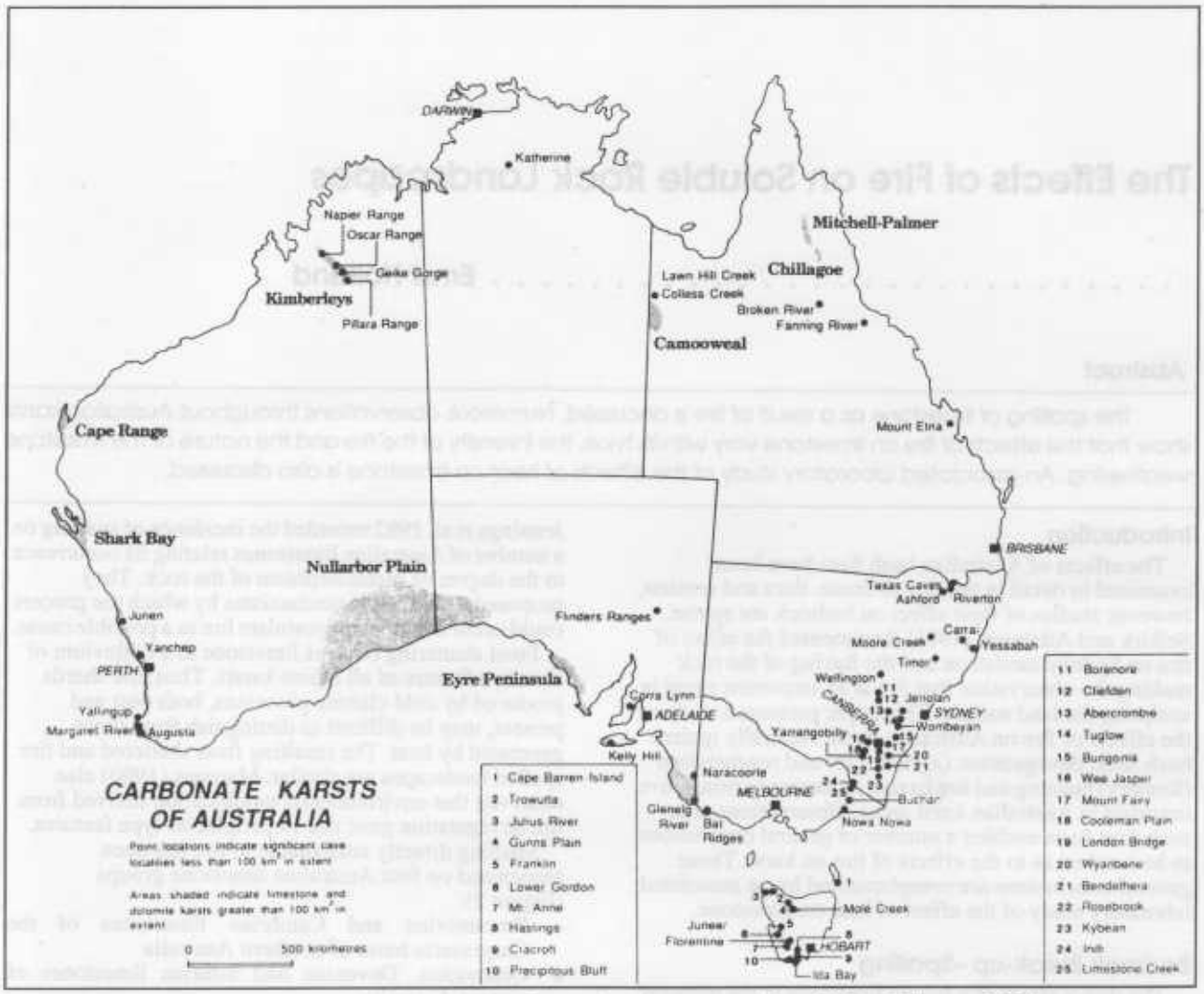

Figure 2. Map of Australia showing the Jenolan Caves study area and karst (after Gillieson 1988).

Plate 1. Spalled shards from Borenore Limestone.

soil display onion skin weathering. Outside in the burnt areas, natural weathering fractures are haphazard.

Not all shards will remain where they are generated by the fire; at Wombeyan Caves NSW shards on rocks with a slope of more than 30° have slipped to the bottom of the slope, where the slope was less than 30° they have remained in position. At Borenore the shards can also be seen accumulated at the foot of the rock slope (Plate 2).

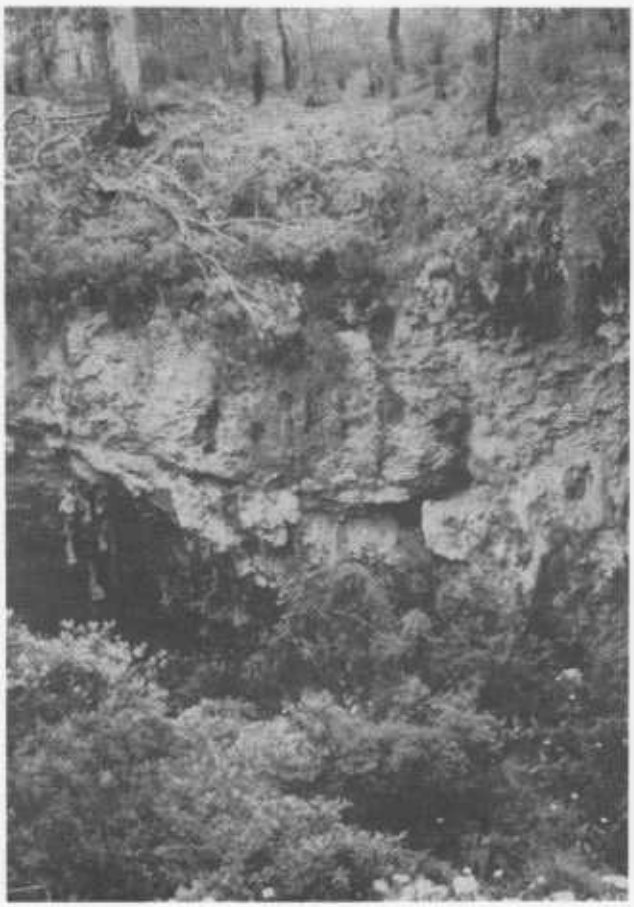

Plate 2. Sinkhole in Western Australia.

Fire had burnt to the edge of a doline at Margaret River, WA and the resulting spalled shards were found below, around the edge of the doline floor (Plate 3).

Plate 3. Spalled material on doline floor.

Spalling destroys karren on limestone. Hamilton Smith et al. (1990) at Cutta Cutta NT, attributes the blunting of sharp edges and minor spalling to the direct effect of repeated fire on the limestone. Spalling and destruction of karren only occurs in hot fires. The destruction is confined to areas of high fuel load, for example, where burnt trees lie across the karren. On the Nullarbor, WA the only fuel load sufficient to generate enough heat to cause limestone to spall is under trees and bushes and burnt areas can be identified by spalling after the trees/bush have been consumed by fire.

At Bendethera, NSW, fire spalling on a limestone already prone to spall has contributed significantly to the production of colluvium. After fire the limestone revegetates with continuous and low cover of *Acacia covenyi*, which when burnt again will produce intense heat close to the limestone surface (Household 1989) breaking up the limestone into small shards and fines.

The lack of karren around the periphery of limestone outcrops in many areas may be a result of fire. Water runoff from an outcrop encourages dense vegetation growth around its base which when burnt generates sufficient heat to cause the limestone to spall and remove the karren.

The Jenolan Caves Study

Limestone samples for the laboratory study were collected in McKeowns Valley, Jenolan Caves Reserve (Figure 2). The area is centred at 33 47'S, 150 05'E, and ranges in altitude from 1200 m at the northern end of the Reserve down to 635 m where the Jenolan River flows across the eastern boundary of the Reserve.

The climate at Jenolan is cool and moist with an average annual rainfall of 800 mm. Wet sclerophyll forest has developed in many of the small side valleys while on the more exposed ridges dry sclerophyll forests predominate. The soils tend to be skeletal on the limestone with low sparse shrubby vegetation.

The Jenolan Caves limestone is Upper Silurian in age and unconformably overlies laminated cherts and andesites to the west and silicic volcaniclastics to the east. The Silurian sequence is unconformably overlain to the east by sediments of the Upper Devonian Lambie Group and the Silurian rocks are intruded by granite plutons north east and south of the caves. Permo-Triassic rocks occur at 1150 m within 3 km of the caves and Lower Carboniferous rocks are overlain by Permian and Triassic sediments 15 km to the east (Kiernan 1986).

The Jenolan Caves limestone is a detrital carbonate sequence and consists primarily of algal-stromatoporal biomicrite and biomicrudite, recrystallised in places to sparry calcite, and is massive, compact and consists of 96-99% $CaCO_3$ (Chalker 1971).

Table 1. Analysis of limestone from the Grand Arch, Jenolan (Lishmund et al. 1986).

$CaCO_3$	97.62%
$MgCO_3$	0.91%
$Fe_2O_3 + Al_2O_3$	0.18%
Gangue	1.04%
Total	**99.75%**

Limestone burning experiments

Samples of Jenolan Caves limestone heated to 800°C in the laboratory exhibited disaggregation from the surface inwards to a depth of 1 cm.

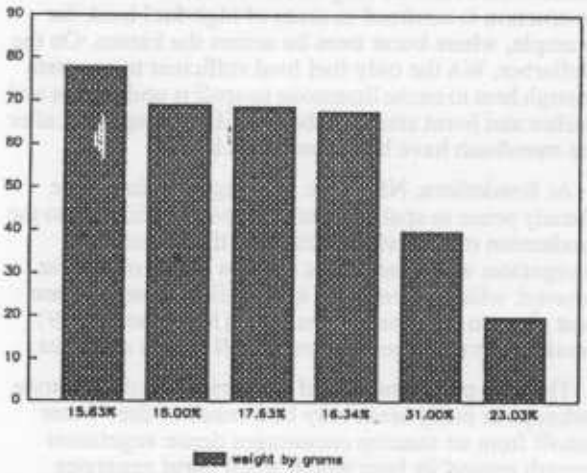

Figure 3. Burn Trial Residues

Loss of weight was variable with the smaller samples exhibiting the greatest weight loss (Figure 3). Carbon dioxide is the major compound lost during burning; other materials and moisture were neither identified nor quantified.

If temperatures from a bush fire are sufficiently high to cause calcining, calcium oxide will be formed and combine with moisture to form $Ca(OH)_2$. Subsequent reaction with carbon dioxide from the atmosphere slowly form microcrystals of calcium carbonate.

$$CaO + H_2O \rightarrow Ca(OH)_2$$
$$CaO + CO_2 \rightarrow CaCO_3 \text{(net equation)}$$

In order to establish whether calcining had taken place during a fire, six limestone shards were collected after the fire and before rain. On immersion in water two of the six samples produced a white compound in the bottom of the beaker (believed to be calcium carbonate).

In all the above samples a release of small grains and other unidentified materials occurred. Microscopic examination of the white compound showed a proportion of silica consistent with the acid insoluble residue and the X-ray diffraction results described below. The process of calcining is expected to release the silica micro-clasts.

Acid insoluble residue experiments

Acid insoluble residues were obtained from Jenolan Caves limestone samples by dissolving them in 3 M HCl and filtering. The acid insoluble residues averaged 0.80% (n = 6) and consisted mainly of silica (quartz).

These values for the insoluble residues agree with the published values by Chalker (1971) and Lishmund et al. (1986) for the Jenolan Caves limestone.

Thin sections

Thin sections were made from samples taken from the study area and examined under a Leitz Ortholux microscope with a heating stage. Emphasis was placed on the muddy facies samples (Plate 4) for the thin sections and X-ray diffraction analysis. Swelling and contraction, possibly due to the loss of water, was observed along the muddy facies under the heating stage. Crystal changes were also noted, possibly due to diffusion creep. Unconformities between different minerals in the muddy facies showed loss of adhesion at temperatures above 160°C (Plate 5). Structural changes were also observed in these areas at temperatures above 190°C. New crystals which developed at 230°C, appear to be a zeolite.

Table 2. Percentage insoluble residue from 3 M HCl digestion of limestone from Century Bluff, Jenolan Caves.

Sample	Weight g	% Insoluble Residue
1	52.01	1.15
2	64.25	0.79
3	65.46	0.82
4	66.94	0.65
5	73.10	0.64
6	73.51	0.77
		MEAN = 0.80

Spalling occurred on all laboratory specimens that were heated to temperatures greater than 550°C and invariably followed linear muddy facies. This observation indicates that clay minerals play a major role in the spalling of limestone allied to muddy layers.

Plate 4. Limestone from study area showing muddy facies.

Plate 5. Loss of adhesion along muddy facies after fire.

Thin sections showed a mineralogical dissimilarity between the fossils and the micritic cement; disaggregation would therefore be uneven allowing the fossils to stand out. Field observations support this. Weathering rates between fossils and micrite would also be different but to date these have not been measured.

X-ray diffraction studies

The X-ray diffraction studies were carried out at the Materials Science Unit, Department of Physics, Australia Defence Force Academy.

The calcite percentage was lower than for the Jenolan Limestone in five of the samples in Table 3 as they were taken from the muddy facies.

The analyses show that the illite group of clay minerals are present and this is supported by the comparatively high birefringence that the samples exhibit under polarized light and reddish brown colours that are common to this group. Illite is a common non carbonate mineral in limestone, for example, X-ray analysis and petrographic studies have shown illite with variable amounts of quartz in the Gordon Limestone (Prasada Rao 1989).

Related studies

Fire spalling also occurs on limestones that do not contain muddy facies. Therefore alternative explanations are required.

The spalling of the calcarenites of Western Australia (Plate 6) suggests that the control may be the case-hardened crust. The porosity difference between the hardened crust and the non-hardened rock can be observed under the microscope. There are a greater number of interconnected pores on the non-hardened limestone. Thus any water held under the crust tends to expand and blow the outer section off when the rock is heated. Borenore limestone has spalled shards from fire (Plate 1) that have the form of large plates with conchoidal fracture around the edges. This type of fire spalling is also seen at Wellington and Molong, NSW. It may relate to moisture content and porosity. Bierman and Gillespie (1991) noted that uneven heating and thermal expansion, in concert with the vaporization of endolithic moisture, induces spalling. The loss of tensile strength near the weathered surface of the limestones may be another explanation.

Boynton (1980) reports that in highly crystalline limestones, the heat produced stress in individual crystals, causes them to fracture. He found that the degree of decrepitation of these crystals maximised with crystals of the largest linear dimensions; with some very large crystals the heat completely disintegrated them to granules. In contrast crystals of 2.5 mm or less generally resisted the temperature stresses. Microscopic examination of limestone from Borenore revealed some fracturing was concordant with individual grain laminae.

Table 3. X-ray diffraction results for limestone from Century Bluff, Jenolan.

Sample	% composition							
	calcite	ferroan	mini-recordite	muscovite	dolomite	quartz	ankerite	unassigned
DT1SOI	98.6	x	x	x	x	x	x	1.4
DT2SOI	22.8	29.9	x	41.5	x	x	2.3	3.4
DT3SOI	16.9	x	x	42.8	27.6	x	3.6	9.1
DT4SOI	57.4	x	x	24.6	x	x	1.5	16.6
DT5SOI	35.7	x	x	33.5	x	24.1	1.1	5.6
DT6SOI	15.3	34.9	2.1	39.9	x	2.3	2.1	2.4

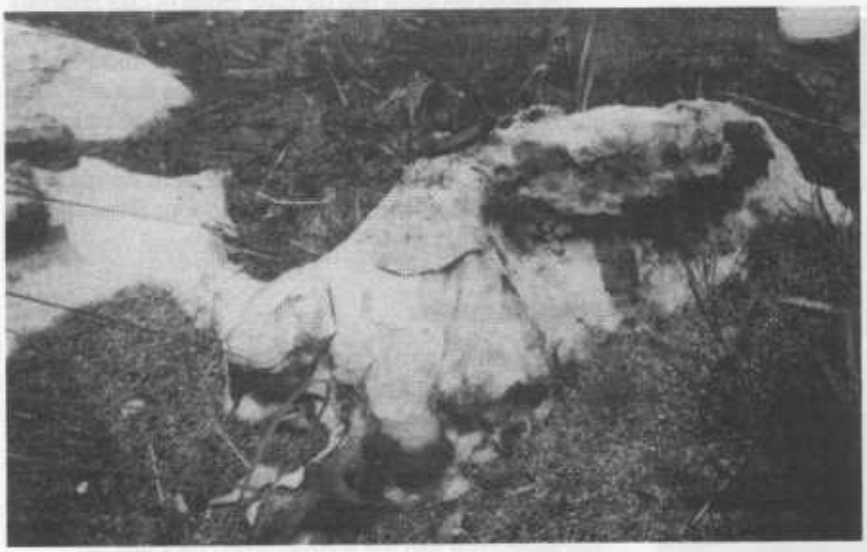

Plate 6. Spalling of calcarenites, Western Australia.

Man, Fire and Erosion on Limestone

In Australia many fires occur naturally and there is ample evidence to show that the incidence of bush fires increased with the arrival of the aborigines and further increased on European settlement. Marker (1975) noted that vegetation destruction and soil stripping was caused by severe bush fires, overstocking and rabbit infestation in the first years after settlement. There is also evidence, mostly anecdotal but supported by some fire records, that naturally occurring fires may be rare on limestone outcrops in the eastern states and on some of our more arid karsts.

Much of our knowledge of the fire history of Australia has come from the study of alluvial and cave sediments. Sediments can give the frequency of the fires from the ^{14}C analysis of charcoal at various depths but may not give the precise location of the fire. A study of sediments in a doline situated in the Playing Fields at Jenolan Caves, revealed a significant amount of charcoal.

> *"Every interval had a significant charcoal component, the charcoal having formed as a result of bush fires. Thus bush fires have been an active feature of the area for a long period of time"*
> (Kelly, 1988).

This charcoal can not be regarded as a signature of fire on the surrounding karst, but rather indicates that there had been a fire in the catchment. Records of fires in the Jenolan Caves area in 1923 and 1957 imply that they passed along the ridges well above the karst yet charcoal from them would have been washed onto the karst to be buried in the sediment record in the Playing Fields doline. This is endorsed by studies in the Elder Cave doline at Jenolan, fire generated shards on the floor have their source on the rim. The uppermost ones are at least 6 cm below the soil again suggesting that no fires have occurred on the Jenolan karst for a long time.

In caves, the accumulation of all charcoal from one fire in one single stratum underground depends on cave depositional processes. Charcoal fragments have been observed to gather in calm waters and because they float a single accumulation may not be the result of an individual fire event. In addition, stratified surface deposits with fire generated layers may be reworked and enter a cave system as a massive mixed deposit of varying age. This reworking of surface deposits has been observed at Jenolan.

In general limestone shards in caves are less reliable evidence of fire than charcoal while fire spalling may be the source, many other processes are possible. It is unfortunate that shards sink and charcoal floats and thus are moved by water to different extents. If they are found in the same sediment the origins of the shards can be confirmed and the site of the fire precisely located.

The break-up of the bed rock mass and soil during fires accelerates sediment movement. The field studies of Harding and Ford (1993) have shown that erosion due to fire is much greater on steeply sloping limestones and that a well developed epikarst aids a rapid recovery of vegetation. They observed that in areas of well developed epikarsts much of the soil and litter, plus other nutrients are retained in the karren troughs and microcaves. It is a paradox that surface erosion due to fire is more severe on karst rocks than it is on others (because of the high density of cavities that catch any detached soil and remove it from sight) yet vegetal recovery on severely eroded sites can be more complete on karst. The exposed karst pavements of the Mount Schank area of south-eastern South Australia, (Plate 7) are a product of a large bush fire that burnt the district in 1939 (pers comm E Hamilton Smith). This extensive bush fire did irreversible damage by loss of topsoil after vegetation removal.

The sealing of epikarst can reduce infiltration capacity and cause rainwater to pond and/or runoff transporting sediments with it. If such sediment ladened waters enter caves, their hydrology can be changed by sedimentation. Watertable caves such as those common in the Tindall Limestone (NT) are particularly prone to sedimentation problems as the incoming waters have far higher sediment carrying capacities after fire than the ground-water outflows. Burning contributes to soil instability both at the surface and at a depth - there is evidence of instability at depth, at Cutta Cutta (NT). Subsidence dolines are found near the Guy Cave and Sculpture Cave outcrops. Subsidence dolines are not unnatural features but their restriction here, to frequently burnt areas, gives rise to concern (Hamilton-Smith et al. 1989).

In Australia karsts are no longer cleared for agriculture by fire as the huge tracts of the Dinaric karst were cleared, for over two thousand years (Gams 1991). However, regeneration burning is still used in the forests of Tasmania to reduce fire hazard, to fertilise the soil for natural reseeding or artificial planting and to reduce competition from shrubs. In the Junee-Florentine forested karst, Tasmania, some very large pieces of spalled limestone were observed after regeneration fires (Plate 8).

Plate 7. Exposed pavements, Mt Shanks, South Australia.

Plate 8. Massive spalling after regeneration fires, Junee-Florentine, Tasmania.

In many Australian karst areas hazard reduction burning to prevent loss of life or property is frequent. So which has the greater impact on karst, a fire resulting from natural ignition or regular controlled hazard reduction burning? The longer the interval between fires, the greater the fuel load the hotter the fire, therefore the greater the potential breakdown of the rock surface. On the calcarenites of southwest Western Australia damage to the vegetation was not as severe on the prescribed burnt area of Margaret River as on the natural bush fire area of Yanchep. However the limestone in both areas had spalling of equal concentration and severity which lead to the conclusion that both fires were not intense.

Harding and Ford (1993) have shown conclusively that intense fires do considerably more damage than cool fires. The soil depth was reduced from 19 cm to 11 cm after an intense burn and to 15 cm after a cool burn and the amount of bare rock was increased from 2% to 40% and 2% to 27%, respectively. The intense fires were believed to have reached temperatures higher than 900°C, the temperature necessary to calcine limestone. The research in this paper supports these observations and in addition has shown in the laboratory that impure limestones can shatter at much lower temperatures.

Conclusions

The degree to which vegetation fires will cause erosion on the limestone has been shown to depend upon the purity of the limestone, its inclination and its degree of karstification. Laboratory studies have shown that the spalling of limestone with clay facies occurs at relatively low temperatures. Harding and Ford (1993) have shown that hot fires do considerably more damage and in some cases short term (until the next glaciation) irreversible damage. Taken in the total context fires are a major component of erosion with the associated potential for ground water disturbance and all fires on limestone should be avoided.

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Hotu Matua's "Island full of holes"

Volcanokarst in the culture and landscape of Easter Island *

. . . . . Kevin Kiernan

Abstract

Volcanokarst is intimately interwoven with the human history of Easter Island. While the caves have been a focus for some archaeological investigation they have been little studied in their own right. The island is entirely volcanic, and lava tunnels are well developed in tholeitic flows which emanated from several vents. The Rolho olivine basalt flow from the small cone of Maunga Hiva hiva is particularly rich in caves. There is limited cave development due to piping of volcanic ash.

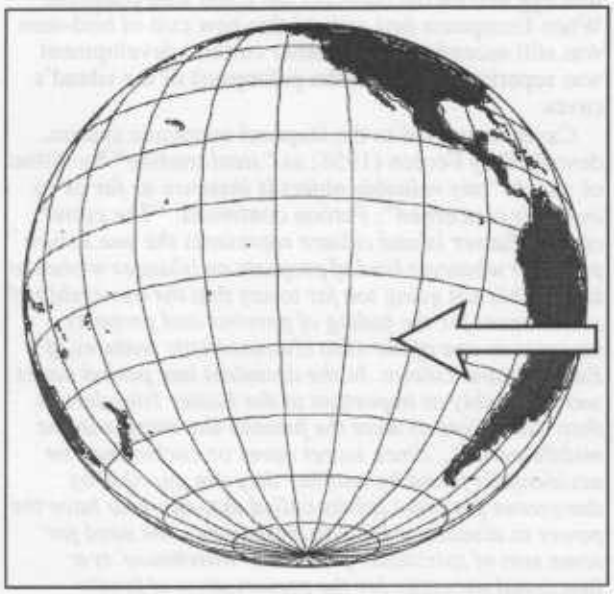

Figure 1. Location of Easter Island

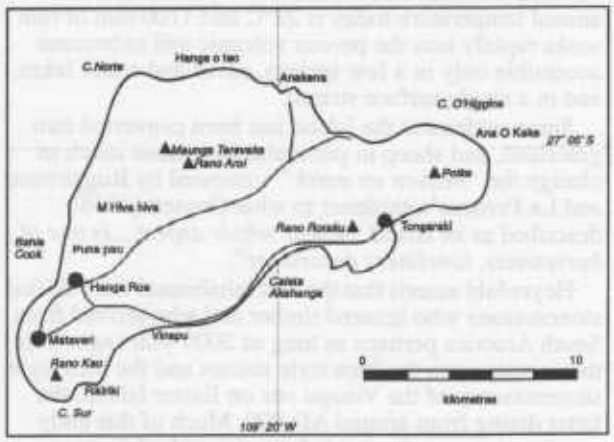

Figure 2. Easter Island

Introduction

In the popular media as to the archaeologist, Easter Island has long been shrouded in mystery. According to folk memory, one Hotu Matua had a vision that led him to dispatch six scouts from his ancestral home of Marae Renga to look for "an island full of holes". Ever since, caves have added to the enigma of the world's most isolated outpost of humanity, a place best known for the giant human statues or *moais* that occur in various parts of the island, notably on the temple platforms or *ahus* which fringe the coastline. The first systematic investigations of the caves by Europeans were those of Thompson (1889), Routledge (1919) and Lavachery (1935). A geologist reported further caves in 1937 (Bandy 1937). A catholic missionary, father Sebastian Englert, visited many caves during his years on the island (Englert 1948). After his epic Kontiki expedition drifted too far to the North to land on Easter Island (Thor Heyerdahl 1958, 1976, Heyerdahl et al. 1961). Heyerdahl published a map that recorded the location of 43 caves visited by his expedition, and the probable location of a further 17 caves reported by the islanders (Heyerdahl 1958). Other caves were located during geological research in the 1960s (Baker 1967). A further 30 caves not recorded on Heyerdahl's map were explored in 1976 (Kiernan 1976). The object of this contribution is to briefly consider the human history of Easter island and the role caves have played, and to review the extent of the volcanokarst.

The isolation of Easter Island is reflected in an ancient name: Te Pito o te Henua-navel (centre?) of the earth. The Dutchman Jacob Roggeveen is believed to have been the first European to sight the island, on Easter Day 1772. The stone age Rapanui people were next visited in 1770 by the Spaniard Don Felipe Gonzales. The speedy disappearance of gifts and stolen items led the Spanish to presume that secret hideaways lay beneath the open landscape. An account by Aguera (1770) noted that *"most of the natives....dwell in underground caves.....the entrances to which are so narrow and inconvenient I have seen them introduce themselves in the opposite manner to what is natural, beginning by projecting their feet and the head last."* In 1774 Captain James Cook saw few people and thought that the islanders must have been hiding in caves, but his men were refused admittance when they tried to examine the boulder piles which they believed hid the entrances. This network of caves was later dramatically demonstrated to La Perouse when the islanders suddenly appeared all over the barren landscape to greet his ship as if they had been spawned by the earth itself. The visitors were permitted to enter some of the caves. As the years drew on the owners of the caves and those who knew their locations were decimated by outsiders and by the internecine strife.

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Volcanokarst in the Culture: The people of the Caves

"The resurrection of an extinct civilisation from a sunken continent to do what the Easter Islanders accomplish unaided is surely the greatest compliment ever paid to an efficient stone age people."

Dr Peter Buck.

Public awareness of the tragic recent history of Easter Island is overshadowed by that of the mysteries posed by its statuary and prehistoric culture. Following internecine strife in his ancestral home, Hotu Matua's small band voyaged to a triangular island 21 x 14 km in extent, with a circumference of 47 km and an area of 160 km^2. Their first home lay in caves at Anakena. Rising to 511 m, at the same latitude as Brisbane (lat. 27°10'S; long. 109°20'W), Easter Island lies on the southern margin of the South-east trades, which blow from October to April and leave the grasslands to bend in waves before more variable winds at other times of the year. The mean annual temperature today is 22°C and 1100 mm of rain soaks rapidly into the porous volcanic soil to become accessible only in a few springs, caves and crater lakes, and in a single surface stream.

Since settlement the island has been converted into grassland, and sheep in particular have done much to change the *"heaven on earth"* witnessed by Roggeveen and La Perouse's gardener to what Gossett (1938) described as an island *"whose whole aspect....is one of barrenness, loneliness dreariness"*.

Heyerdahl asserts that the first inhabitants were skilled stonemasons who ignored timber and who arrived from South America perhaps as long as 2000 years ago. This thesis rests upon the Inca style statues and the Inca style stonemasonry of the Vinapu site on Easter Island, the latter dating from around AD 800. Much of this early construction was dismantled to retrieve building materials during later cultural phases. However there is considerable cultural unity with Polynesia. Radiocarbon dating indicates that man from SE Asia had reached the Solomon Islands by 5,000 years BP, and New Caledonia and Fiji by 3,000 years BP. He reached the Marquesas by AD 400 and extended into the Easter Island, Hawaiian and New Zealand extremities of the Pacific triangle after AD 500. Megaliths remained behind in the Marquesas, Tonga, Easter Island, and on the coast of Peru. Did some of the South American culture come from the Pacific? Yet Heyerdahl cites a radiocarbon date of AD 380 from Easter Island and recently discovered coral and obsidian eyes that fit some of the *moais* appear to be of South American affinity. Perhaps Easter Island welcomed settlers from east and west.

The people encountered by Roggeveen appeared to comprise two groups. Some were red haired and tattooed, their ears deformed like those of the *moais* through elongation of the earlobes by heavy weights. These people were the Tu'uaro and Hotuiti people (variously referred to at the "long ears" or "thin" people) who tilled the thin stony soil. Among them were the Hanaueepe ("short ears" or "fat" people - again depending upon the authority consulted) who fished the seas around Easter Island. While Heyerdahl argues that South Americans were the first migrants, it is generally argued that the "long ears" arrived first. It seems clear at any rate that the short eared Hotu Matua was part of a second wave. The islanders then dwelt in rush huts, fished and cultivated sweet potatoes. The existence of the *moais* implies a high degree of social organisation for enormous energies were diverted away from food production. The carvers were still at work in AD 1470. But in the 17th - 18th century strife broke out, possibly due to diminishing crops during the Little Ice Age (McCall 1981). Weapons are absent from archaeological deposits before AD 1680, but suddenly obsidian spear points littered the ground. The "short ears" resisted the demands of the "long ears" to help clear the soils of rocks, promoting what was probably the only major battle before the arrival of the Dutch. Hundreds of skeletons with broken bones and carved skulls attest great violence and are to be found in the caves and elsewhere. The Rapanui fled underground, often using the foundations of their former reed houses for construction purposes in the caves. Food production ground to a halt and starvation took over. The sufferings are reflected in wooden carvings of emancipated figures with protruding ribs which have been found in the island's caves. The old deities were of little assistance. Strangers arrived in great ships. Violence met despair and compounded it. The *moais* were overturned, probably around the 1860's. Now the seasonal arrival of terns became important to the diet of the Rapanui. The tern came to be worshipped. Hereditary kingship was replaced by a system of annual competition to obtain the first egg laid on the islets off the Rano Kau coastline. When Europeans first arrived this new cult of bird-men was still ascendant. Yet another cultural development was superimposed upon the palimpsest of the island's caves.

Caves were vital to the Rapanui economic system, described by Ferdon (1958) as *"steal trading"* by virtue of which *"any valuable object is insecure as far as its owner is concerned"*. Ferdon continued: *"The secret cave in Easter Island culture represents the one secure place for whatever kind of property an islander wishes to keep....It is not going too far to say that the ownership of secret caves for the hiding of persons and property emerges as one of the most characteristic features of Easter Island culture. In the decadent late period caves were probably as important to the Easter Islanders in their daily lives as were the famous* ahu *images in the middle period....Since secret caves or caches may be accidentally found by another they are guarded by dangerous personal spirits called* aku-aku *who have the power to disable or kill any trespasser....the need for some sort of spiritually protected 'warehouse' is a functional necessity for the preservation of family heirlooms and capital assets."*

Volcanokarst in the Landscape: Cave Exploration

Thompson (1889) observed that *"natural caves are numerous both as the coast and in the interior of the island"*. His was the first European party in pursuit of archaeological relicts to explore caves on Easter Island (Heyerdahl 1976). he recognised caves that were *"worn by the action of waves"* as opposed to others that were *"due to the expansion of gases in the molten lava and other volcanic action."* He continued:

"Many caves were reached after difficult and dangerous climbing and were found to contain nothing of interest while others of traditional importance were inaccessible from below and were not provided with ropes and the necessary appliances for reaching them from above....Some of the sea-worn caves are of considerable extent but generally difficult of access and affording little of interest except to geologists. The caverns produced by volcanic agencies are found throughout the island and some were traced through subterranean windings to an outlet on the bluffs overlooking the sea. They were generally quite dry. The rainwater falling upon the surface occasionally finds its way between the cracks or joints in the solid rock, but these gloomy passages and chambers lack grandeur from the entire absence of stalactites and decorations of carbonate of

lime. No glistening and fantastical forms of stalagmitic decorations exist here to excite the fancy and create the imagination scenes of fairy-like splendour. The feeble rays of our candles were quickly absorbed by the sombre surroundings, heightening the apparent extent and gloom of the recesses."

The archaeology of these caves also drew the attention of Katherine Routledge in 1914, whose party *"daily examined such caves and grottoes as came under our notice"*, but she too complained of her *"inability to reach the most thrilling of the caves, which are half-way up the great sea cliffs"* (Routledge 1919). In her footsteps came a Franco-Belgian expedition in 1934 (Lavachery 1935).

Many caves were known to the late missionary Father Sebastian Englert. Among a number of notable explorations by Father Sebastian was that of the 400 m long Ano-o-Keke at the eastern end of the island. Father Sebastian's Rapanui housekeeper and her sister-in-law were keen cave hunters who greatly assisted him in his documentation of Easter Island's antiquities. His book on the island recorded the use of caves for residential purposes, for burial and for refuge. He referred also to:

"secret caves which were the property of particular families and only the most important persons in a family knew the entrance to their respective secret cave. These served as hiding places for valuable things, such as inscribed tablets, rongo-rongo or statuettes. The secret of the exact location of the entrance is buried in the graves with the last survivors of the old times." (Englert 1948).

Although Father Sebastian had failed to gain access to any of these family caves, the Norwegian party under Thor Heyerdahl which spent several months on Easter Island in the mid 1950's confirmed not only that they existed but that they continued to be respected and maintained by the islanders. Within such caves the archaeologists found carvings of wood and stone, often wrapped in or sitting on reed mats, together with stone containers and skeletal remains of forbears. Other caves contained fish shells, bird, rat and turtle bones, amulets of bone and shells, and needles of human bone. Considerable ceremony was attached to entry into caves. Even after the ceremonial transfer to Heyerdahl of one cave's contents, the former owner retained the cave itself *"in case of war"*. Indeed long after burial in the Hanga Roa village cemetery had become compulsory there were still instances of elderly islanders stealing away to die alone in their family caves. Only the few remaining descendants of the "long ears" maintained family caves. Subsequent archaeological studies to which I do not have access have presumably continued some investigation of caves. However while caves are abundant and many are easily found this is not always the case. Small entrances in steep cliffs provide a natural difficulty exploited by the selection of secret family caves. Entrances to other caves used to store family treasures or provide refuges during the fighting were deliberately hidden:

"Atan...pointed straight to the ground at the tips of my toes. I saw there a small flat stone half covered with sand and loose straw, exactly like 10 million others nearby."

(Heyerdahl, 1958 p226)

Easter Island is characterised by countless billions of scattered rocks, any of which might deliberately cover caves. Although Heyerdahl doubted the veracity of some guides who failed to locate alleged caves, it is as well to remember how frequently cavers manage to lose caves in bush without the additional obstacle of their being deliberately hidden. On Easter Island in 1976, I was myself extended the utmost hospitality and friendliness by the Rapanui, but on the other hand there was zero co-operation as far as caves were concerned - indeed the very existence on the island of **any** caves whatsoever was strenuously denied, even though entrances lay agape for all to see around the outskirts of the village. Whether the veil of silence was due to a continued desire to protect family caves or perhaps to debunk any suspicion of the old beliefs still being held remains open for debate. Alternatively, it may be noteworthy that on my departure I was taken aside by armed officials and thoroughly searched - I record the fact not in protest but in appreciation that the authorities apparently no longer intend to permit the sort of archaeological plundering that has robbed Easter Island of too much of its heritage. Perhaps before any speleologist risks trampling underfoot the sensitivities of the Rapanui it may be as well to recount an anecdote recorded by Heyerdahl (1958, p210).

"I had said that sometime in the future it would be possible to find the secret caves and tunnels of the island by going over the ground with a kind of cavity detector. This made a strong impression on Lazarus. As we rode along he pointed out several areas in which such an apparatus would be effective because there were supposed to be secret caves under the ground, of which the openings had been lost. He declared with dismay that the first person to bring the apparatus to the island would get rich simply by walking among the houses in the village. A secret cave 300 yards long which had belonged to one of the last kings ran underground to the sea from an unknown spot near the most northerly houses. It was found by a man who brought up some gigantic spear-heads from the cave, but the aku-akus bit and pricked him night after night until he died."

Preoccupation with the search for family caves and archaeological deposit has meant that caves have been undervalued as remarkable landforms in their own right. Heyerdahl's (1958) account reflects on the morphology and size of some of the non-secret lava tunnels:

"Later we visited several of these huge caves with room after room like pearls on a string running down through the underworld. Their entrances were all so skilfully walled up that no-one could get down through the narrow funnels cut with sharp angles or zig-zags, in which any assailant would be completely helpless. There was water in some of the largest caves; two of them had regular subterranean pool and right down at the bottom of a third we found a walled well of ice cold water surrounded by a stone pavement and a well built terrace some ten feet high."

Although caves have been mentioned by at least two geological workers on Easter Island (Baker 1967, Bandy 1937), the only other paper known to the writer that specifically focuses upon the caves is his own brief review of his limited explorations in 1976 that may have introduced Easter Island to the speleological literature for the first time (Kiernan 1976). This exploration focused upon the Roiho flow, the lava flows to the east and south, a small area on the north-west slopes of Rano Kua, and also upon the piping caves of Rano Aroi and sea caves around Hanga Roa. As intriguing as secret caves may be to archaeologists and treasure hunters, they provide only a sidelight to the story of Easter Island and it's caves, for the island abounds with more obvious and less sensitive entrances. This is accurately reflected by Heyerdahl's comment that *"on the first day we were n and out of caves from morning to night"* and as Gossett (1938) observes, the shore of Easter Island is *"honey-combed with caves in the lava"*.

Volcanokarst in the Landscape: The lavas and some caves

Easter Island lacks continental rocks. Although conglomerate was recorded by Braun (1924), the material he described is a tuff. But for some calcareous sand at Anakena, the traditional landing place of Hotu Matua, and at an equally picturesque beach 2 km to the East, the island is entirely volcanic. It is surrounded by oceans 4,000 m deep. The island's geology is described by Baker (1967), Baker et al. (1974), Bandy (1937) and Gonzales et al. (1974).

The basalts of Easter Island are tholeitic but range between quartz normative and olivine tholeites (Baker et al. 1974). They are low in MgO but high in T, Zr and total Fe. A low K content is also characteristic. Three large volcanoes - Poike, Rano Kau and Maunga Teravaka - stand at the corners of this triangular island. About 70 lesser eruptive centres are known. Much of the coastline comprises high cliffs on the flanks of the cones, but to the South it is formed by a single flow only a few metres thick. Although various caves have been entered both by islanders and visitors I am unaware of any cave inventory, and the following only scratches the surface of what is already known but which seems to be mostly unrecorded.

Poike

Poike is a strato volcano from which a K/Ar assay of 3 my BP has been obtained. Poike comprises the oldest section of Easter Island. Trachyte is associated with the parasitic domes of Maunga Vai a heta, Maunga Tea-tea and Maunga Parehe, but the northern cliffs are highly porphyritic basalts or hawaiites with plagioclase phenocrysts. Aphyric lavas lie to the SW. Poike was formerly a separate island. Lava caves occur right around the Poike coastline, the best known lying on the northern side.

Ana o keke (Cave of the White Virgins; Cave of the Sun's Inclination) lies east of Katiki volcano. Its small entrance lies in a steep sea cliff. This cave contains about 400 m of passages, some of which are narrow and wet. Human remains lie in a dry inner chamber. Young girls were confined in the darkness of this cave to bleach their skin to match the fairness of the gods. Here their religious training included learning to recite from the *rongo-rongo* - wooden tablets with now indecipherable hieroglyphics of which no more than 20 are known. Several are reputed to have survived a smallpox epidemic because of their isolation in Ana o Keke, only to die of starvation when there was no-one to bring them food. In this same area lies a residential cave. A spring supplies the water that is led into the massive mouth of a giant head carved into the rock wall nearby. Other caves and a spring from a deep fissure lie east of Maunga Tea-tea. Further caves occur on the SW side of Maunga Vai a heva, in the sea cliffs on the south eastern extremity of Poike, and at least one on the island of Marotiri.

Rano Kau

At the western extremity of Easter Island stands Rano Kau. Its impressive caldera of 1.5 km diameter contains the large lake from which this volcano derives its name. Sea cliffs of 300 m mark its western flank. Thin basaltic lava flows are interbedded with pyroclastic material at the base of Rano Kau and are overlain by more differentiated lavas. Benoreitic flows form the upper caldera wall. These break into flat slabs that were used to construct low stone houses for the "bird men" of Orongo. The lower basalts provided much of the dressed stone to construct the Ahu Viahu. White trachyte and rhyolitic obsidian are associated with a parasitic centre on the north-eastern slopes, and rhyolites with the "birdman" islands of Motu iti, Motu nui and Motu kao kao. The obsidian of Maunga Ourito and Maunga Otu is generally a clear, greenish brown glass with conchoidal fracture. Man has scattered the obsidian widely across Easter Island in the form of stone tools.

One of the best known caves of Rano Kau is Haka-Rongo Manu (Cave of Listening for the Birds). This lies partway down a steep sea cliff below Orongo. During the bird-man phase it was here the Rapanui waited for the arrival of the first *manu tara* tern (*Sterna fuscata*) to reach the bird-man islands. Nearby lies Mata te Paina (Eye of the Straw Image), a closed cave in the cliffs. Still other caves occur around the NE crest of Rano Kau, and numerous other rumoured caves were presumed by Heyerdahl to lie in the sea cliffs, particularly in the Rikiriki-Vinapu area. A number of caves occur on Motu nui some of which contain human bones. Two were visited by Routledge. In another, Heyerdahl found statuettes, including a red head with a goatee beard.

Maunga Teravaka

Rising to 511 m on the northern corner of Easter Island is the complex fissure volcano of Maunga Terevaka, the island's highest summit. Flows up to 15 m thick occur here, and K/Ar assays of up to 300 K yrs. BP indicate this to be the most recent of the large volcanoes. A U-shaped system of ridges opens to the North comprises coalesced pyroclastic cone, the largest of which is Rano Aroi. Rows of craters extend SSW from the southern slopes of Maunga Terevaka to Maunga Otu'u, the hard dark lavas of which were much favoured for stone tools, including carved fish-hooks. A further line of eruptive centres extends WSW from the western flank of Terevaka to Rano Raraku where a wave-cut notch in the SE rim about 1 km from the present coastline may mark a high sea-level stand, probably of Last Interglacial age.

The *moais* were carved from the yellowish-brown sideromelane tuff of Rano Raraku. This centre originated as a submarine vent that discharged palagonitic tuff and ash and some lava. The tuff comprises vesicular glass fragments enclosing small crystals of plagioclase, olivine, chnopyroxene and opaque oxides. Basaltic xenoliths and scoriaceous fragments occur in a calcareous cement. Carving projects were occasionally abandoned due to xenoliths, although many of the inclusions were then utilised for stone tools. Most of the lava flows are of hawaiite composition. A pale aphyric flow from Maunga Hiva hiva near Roiho is an olivine tholeite. It contains phenocrysts of olivine and is more alkaline than the other lavas of Easter Island. Further to the south-west are lavas that are similar in composition to those of Rano Kua but which appear to have been emitted from the Terevaka complex: their origin is not clear. In this area lies the 100 m high and 300 m wide cone of Puna pau. All the *maroke* or top-knots that adorned many of the *moais* and symbolised red hair or headgear were fashioned from this scoriaceous rock, which is brackish when fresh but weathers to a bright red colour.

Over 80% of the known caves of Easter Island lie in the Maunga Terevaka lavas. Ana Hotu Matua (Hotu Matua's Caves) lie in a small gully in the Anakena Valley. These spacious chambers are traditionally believed to have sheltered Hotu Matua's party when it arrived at Anakena, before the first reed huts were constructed. They are still occasionally slept in by islanders. Nearby stand the *moais* of Ahu Anakena, the first of which was re-erected by William Mulloy during the Norwegian expedition, and the others by a Rapanui archaeologist, Sergio Rapu.

The coastal strip from just west of Anakena to a point west of Maunga Kuma is a highly restricted zone in the management plan for the Parque Nacional Rapa Nui

(Zentilli 1977). Motu Tavake (Cliff of the Tropical Bird; Lazarus' Cave) lies in this area at Omohi, west of the Hanga-o-Teo plain and at the foot of Vaimataa. It is difficult of access, its entrance being a narrow squeeze hidden under a projection in a 50 m sea cliff. Sculptures were collected from this cave by Heyerdahl. Nearby is one of several snake carvings known on the island, in a part of the world where snakes are unknown.

The entrance to a family cave recorded by Heyerdahl (1958) as "Mayors Cave N°2" is a horizontal crack that lies 20 m from the top of a 100 m sea cliff near the Anu Tepeu. Within it he found numerous stone carvings, some of which he speculated may have come from the nearby *ahu* to be hidden in the cave during the wars. This lies amid the mugearite and benmoreite flows of Rano Aroi.

Various other caves have been reported around the coast facing slopes of Terevaka. Two family caves are reputed to lie above Vaitara Kaiva. Another is known in a cliff at Hanga Hemu and another at Hanga-o-teo. Many more caves lie in the Maunga Ha'u epa - Maunga Te Puha roa - Maunga Kou'a area to the East of Anakena, and at inland locations between here and Rano Raraku. At the latter location a cave in the rock face is reputed to contain three sections, each of which was maintained by a family. Another cave lies at Hotuiti.

Along the coastline between Poike and Rano Kau are a number of caves, some of which contain human remains (Kiernan 1976). Secret caves have also been reported in this area (Heyerdahl 1958). One of these is supposed to be at Vinapu and another at Hanga Maihiku. "Santiago Cave" (Heyerdahl 1958) is entered through a narrow hole and contains stone sculptures. A residential cave near an *ahu* in this locality has well-constructed stone steps leading into it (Kiernan 1976).

A moderate sized cave lies in the sea cliffs west of the airstrip. In the area of mugearite and benmoreite flows nearby lies Ana Kan Tangata (Cannibal's cave). various secret family caves are rumoured to exist beneath the Hanga Roa village, not all of which are taboo. Heyerdahl examined at least three of the caves in this area. "Mayors Cave N°1" lies just inland of the route from the village to the leper station, and two or three others, including "Enliques Cave" near the Ahu Paro. In this general area what appears to have been an old residential cave now shelters sheep, as indeed do many of Easter Island's Caves (Kiernan 1976). "Wizards Juan's Cave" lies east of the road 1 km south of the leper station.

Raakau ("Atans Cave") is named for the moon. Its entrance was shown to Heyerdahl, who collected many of the sculptures that lay on reed mats: *"here were curiosities which would make any art dealer tear his hair in excitement.... fabulous underground treasure chamber"*. The cave lies north of Puna pau. There are numerous small shelter caves in this area. Off the western coastline on Motu Tuatara are two burial caves, in one of which a member of the Norwegian party found red hair still intact on a human head.

However by far the most densely cavernous single area on Easter Island appears to be the olivine lava flow from Maunga Hiva at Rioho (Baker 1967, Kiernan 1976). Baker remarks upon *"the extraordinary ramification of lava tunnels and tubes which occupy its interior"*. The surface of this triangular-shaped flow, which covers about 3.5 km^2, is pockmarked by enclosed depressions about 10 m deep. Some have coalesced to form small pseudo-uvulas, the largest of which measures about 200 x 50 m. An entrance through talus beneath the low cliff at the northern end gives access to a spacious cavern 10 m high, but inadequate lighting equipment prevented full exploration of this cave by Kiernan (1976). Caves frequently open off either end of a single sink-hole formed part way along a tunnel. Further to the west a lofty passage extends from a 4 m high entrance in another sink-hole. At least 20 cave entrances occur in this vicinity. Some contain old man-made terraces while in others, stone walls have been constructed, presumably to block off passages and alcoves.

Volcanokarst by Piping

A final series of caves in the Terevaka area is of quite different origin. Surface water is scarce on Easter Island. Springs below sea level were sometimes were drawn up directly by the Rapanui, and sometimes intercepted by wells dug in beaches. Precipitation rapidly sinks into the porous volcanic ash, sometimes to reappear as springs where it is brought to the surface by basalt flows. Pools of water in lava tunnels must also have been important, to judge from the artificial channels and collecting depressions carved in the stone floors of some caves. Some pools near entrances are today fouled by stock. Some surface water is also held in crater lakes.

The only surface stream is that which flows from the crater lake of Rano Aroi. Here piping of volcanic ash has produced a large underground conduit. Partial collapse has produced a 10 m deep gully spanned by natural bridges. Bandy (1937) recorded that many of these caves were large enough to admit a man on horseback, but by 1976 much of the system had collapsed to leave the gully spanned in only four places (Kiernan 1976, 1980). These may be the only penetrable caves on Easter Island that are the product of running water.

Overview

The lava tunnels of Easter Island are of late Tertiary to late Pleistocene age and are formed in fluid pa hoe hoe lavas of tholeitic composition as exemplified at Rioho. Detailed speleogenetic studies have not been undertaken but a few general comments seem possible. The lava in which some of the caves are formed is layered. It is difficult to escape the argument of Ollier (1975) that if the lava in the tubes has eroded the layers, as appears to have occurred in some cases here, then the layers must predate the tubes. Thus in at least some cases on Easter Island the hypothesis of Ollier and Brown (1965) seems preferable to formation by the crusting over of surface channels as described by Peterson and Swanson (1974). Evidence exists within those caves observed by the writer for fluvial-type downcutting by prolonged lava mobility after the roof had developed. Flat floors are common and suggest incomplete drainage in some cases, as do convexities in the longitudinal profiles of cave floors probably formed due to pressure differentials in the liquid lava rather than degassing. Some passage infilling by congealed lava has occurred at a late stage the size of the tunnels and moderate gradient suggests fairly rapid flowage of the fluid rock. Elongate chambers are often linked by low roofed crawls. This form may be related to the formation of flow units (Nicholls 1936) and/or hydrostatic pressure.

Concentric shelling of the lava parallel to cave roof profiles is commonly exhibited at cave entrances. The tunnels are exposed both by surface collapse due to sub-aerial erosion and through truncation of lava flows by marine erosion. Angular blocks on the cave floors reflect secondary breakdown and are most common near entrances. Some tunnels are known to reach 400 m in length. Only small lava stalactites are known to the writer, most little more than botryoidal.

Piping of volcanic ash has resulted from the rapid absorption of rain into the soil, and the overflow of the Rano Aroi crater lake. These piping caves are best developed along the course of the Rano Aroi stream, but a similar process of spring flushing is responsible for micro caves elsewhere, particularly when resistant lava

intercepts the passage of underground waters through the pyroclastics.

Similar differential erosion of the pyroclastic and lava rocks by the sea has developed broad shallow caves around various parts of the coastline. Some shallow caves inland, particularly around Rano Raraku, may be due to marine erosion during former high sea level stands. Differential erosion by sub-aerial processes has been responsible for some shallow rock-shelter caves elsewhere on Easter Island.

The caves of this lonely island have attracted negligible attention from speleologists. Instead, they have provoked some interest from archaeologists seeking to resolve a popular enigma. The caves of Easter Island form a palimpsest upon which is recorded the human experience of man's loneliest and most remote outpost. It is this that provides perhaps the greatest fascination in the netherworld of Hotu Matua's "island full of holes".

"Everywhere is the wind of heaven; round and above all are boundless sea and sky, infinite space and a great silence. The dweller there is ever listening for he knows what, feeling unconsciously that he is in the antechamber to something yet more vast which is just beyond his ken."

Katherine Scoresby Routledge, (1919)

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Crombie's Cave. A granite cave in New England, NSW

C.D. Ollier and J.M.B. Smith

Abstract

Crombie's Cave is a small cave near Armidale, NSW, formed when Powers Creek found an underground route through weathered joints in granite, and enlarged by stream abrasion.

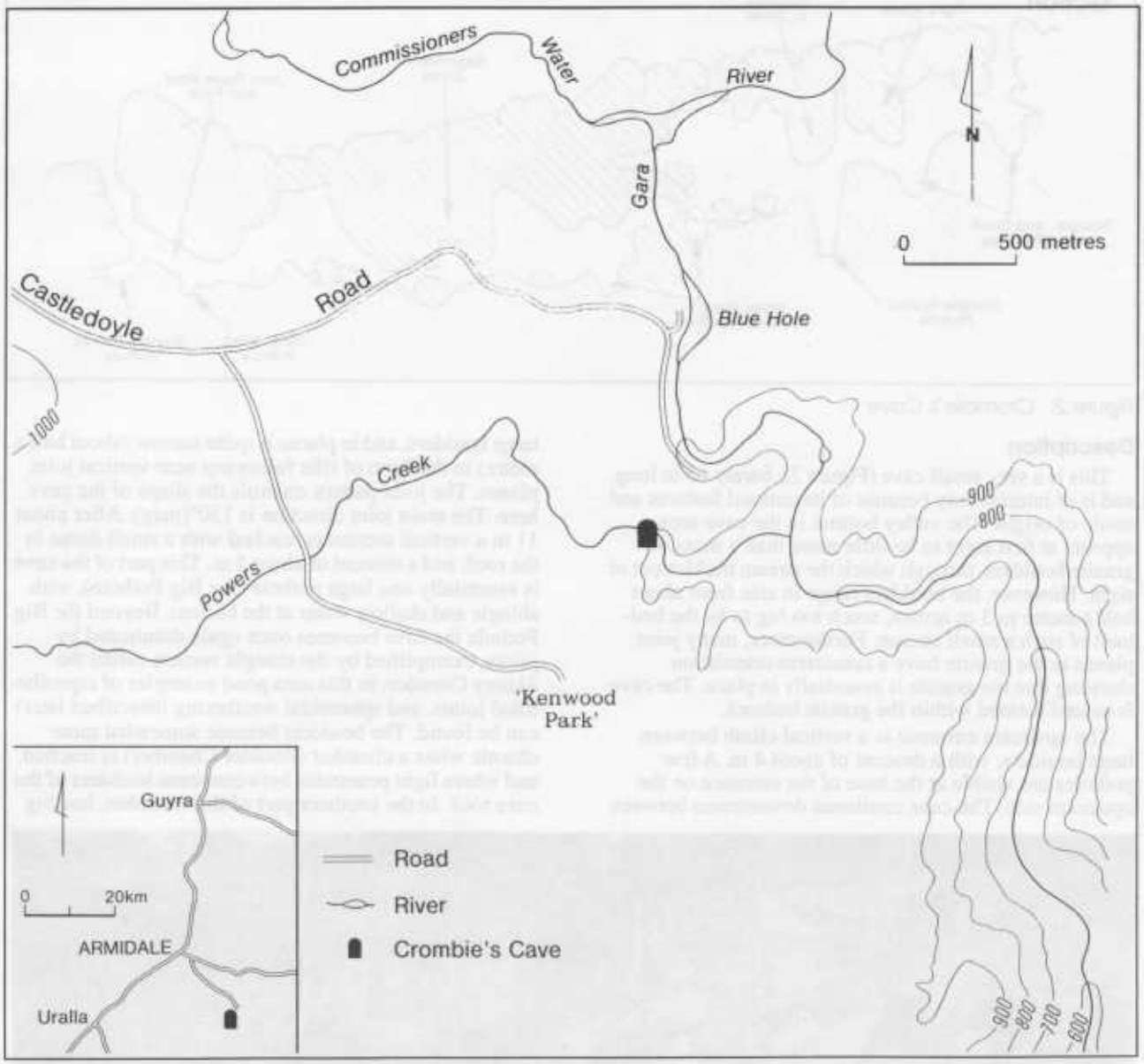

Figure 1. Location of Crombies Cave

Location

Crombie's Cave is located near the end of Castledoyle Road about 16 km eastsoutheast of Armidale on the northern tablelands, New South Wales, at an altitude of 900 m. It is in an area of Crown Land covered by a grazing lease, between the Gara section of Oxley Wild Rivers National Park and the property "Kanwood Park", at 846136 on the Hillgrove 1:250000 map (sheet 9236-1-N). It lies about one kilometre south of the well-known recreation site Blue Hole, and is most easily approached from that direction (Figure 1). Passing through the cave is the transient stream Powers Creek, a tributary of the Gara River into which it flows about 800 m downstream of the cave, in the upper reaches of Gara Gorge.

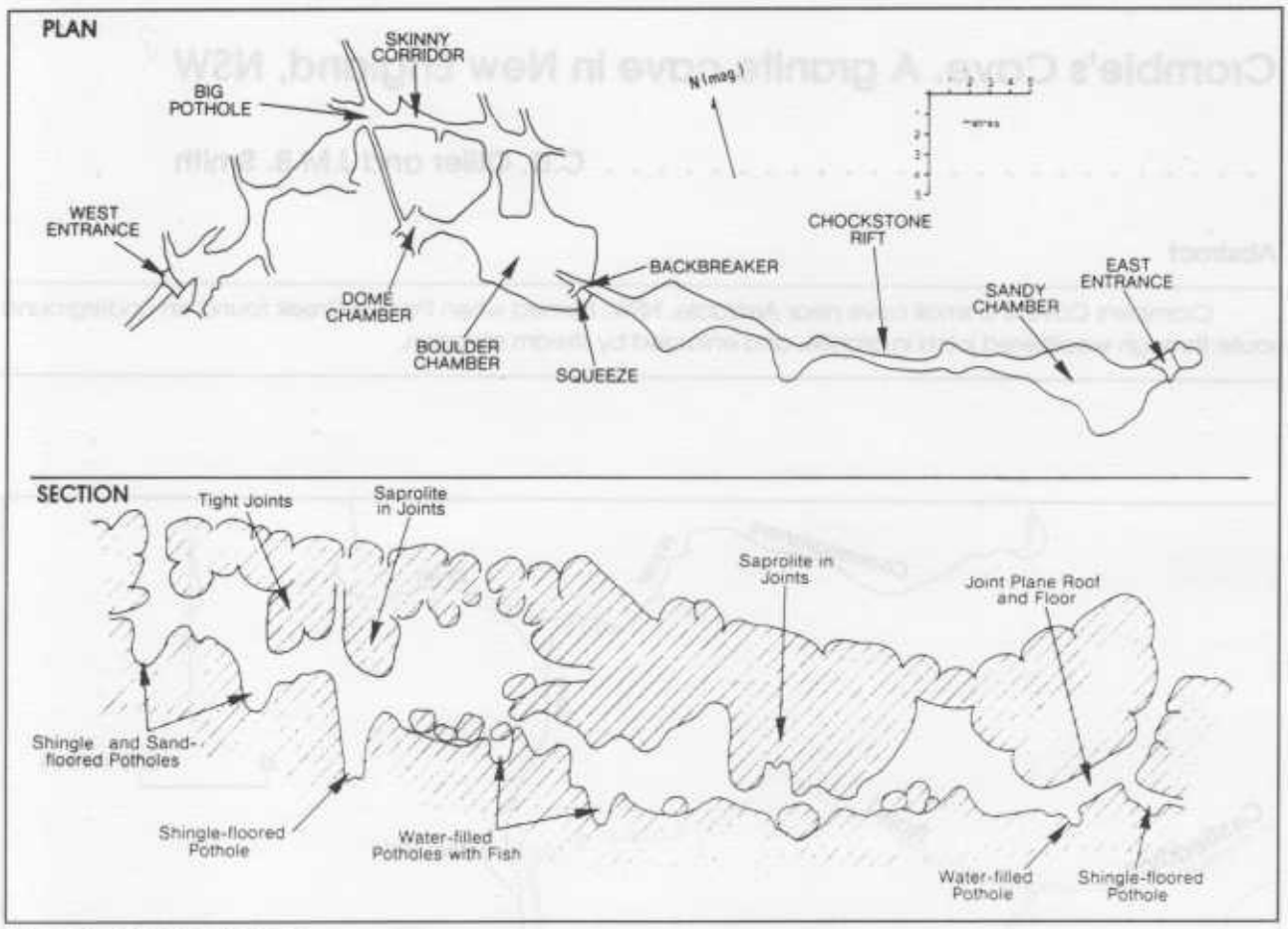

Figure 2. Crombie's Cave

Description

This is a very small cave (Figure 2), barely 65 m long, and is of interest only because of its unusual features and mode of origin. The valley bottom in the cave area appears at first sight to be little more than a mass of granite boulders, through which the stream trickles out of sight. However, the boulders range in size from about half a metre to 5 m across, much too big to be the bed-load of such a small stream. Furthermore, many joint planes in the granite have a consistent orientation showing that the granite is essentially in place. The cave is indeed formed within the granite bedrock.

The upstream entrance is a vertical climb between large boulders, with a descent of about 4 m. A few potholes are visible at the base of the entrance on the upstream side. The cave continues downstream between large boulders, and in places is quite narrow (about half a metre) in the form of rifts following near-vertical joint planes. The joint pattern controls the shape of the cave here. The main joint direction is 130°(mag). After about 11 m a vertical section is reached with a small dome in the roof, and a descent of about 5 m. This part of the cave is essentially one large pothole (the Big Pothole), with shingle and shallow water at the bottom. Beyond the Big Pothole the cave becomes once again dominated by joints, exemplified by the straight section called the Skinny Corridor. In this area good examples of saprolite-filled joints, and spheroidal weathering (described later) can be found. The boulders become somewhat more chaotic when a chamber (Boulder Chamber) is reached, and where light penetrates between some boulders of the cave roof. In the southern part of this chamber, leading

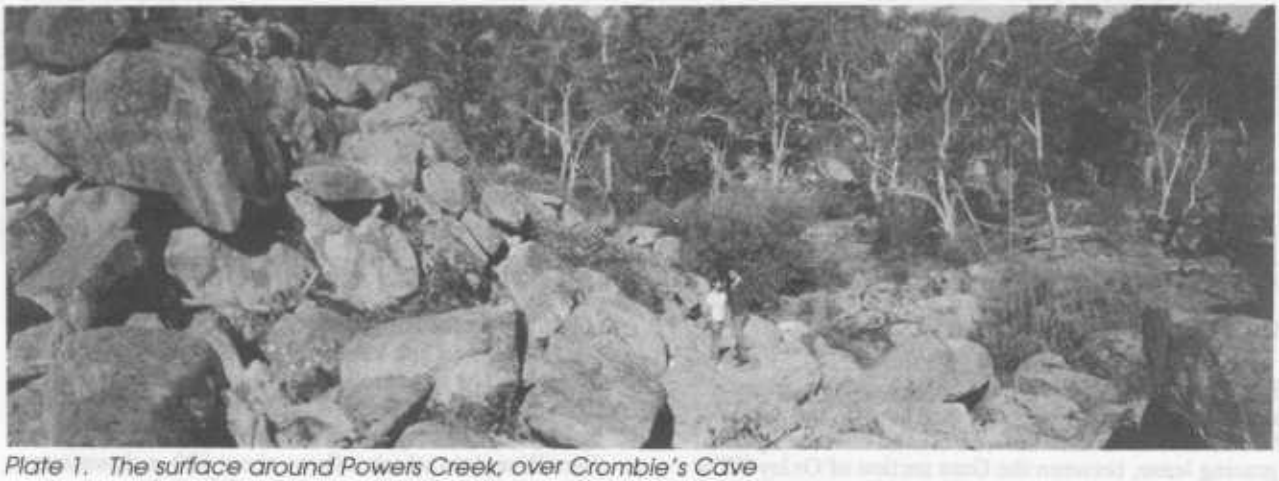

Plate 1. The surface around Powers Creek, over Crombie's Cave

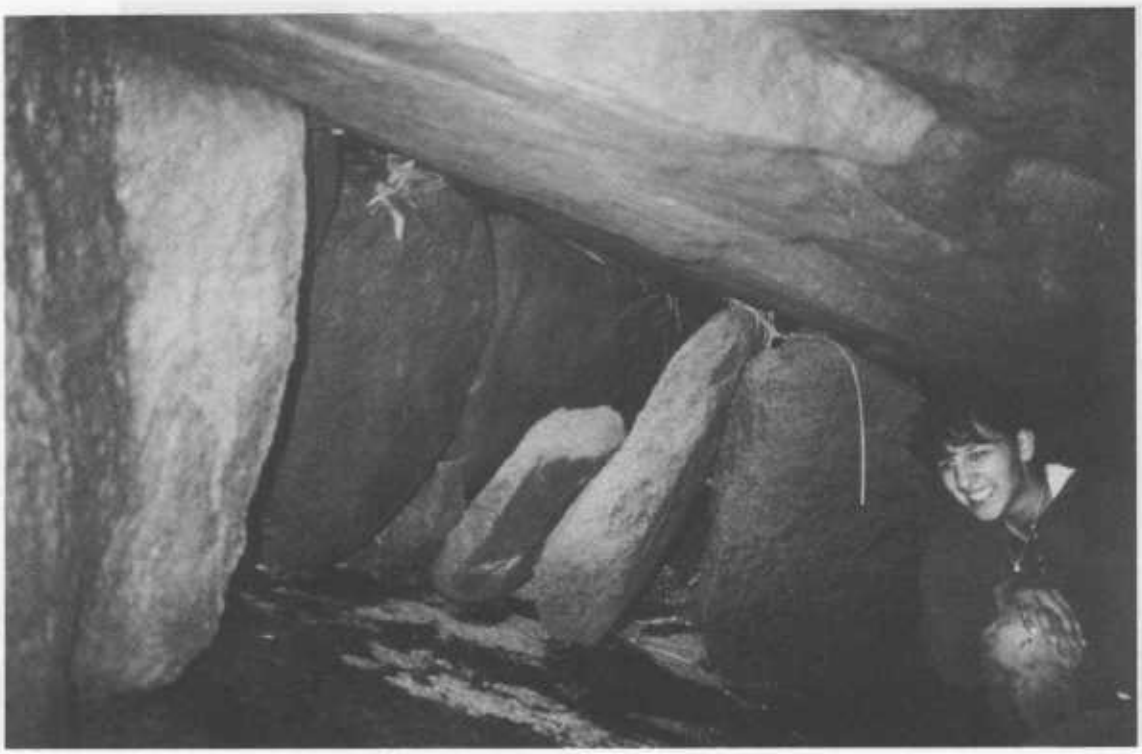

Plate 2. Angular joints in Sandy Chamber

out of a depression between two boulders, occur two alternative routes through to the next, lower section of the cave. The route usually taken is a narrow, unpleasant crawl called the Squeeze which leads directly into a narrow slot containing a chockstone (the Back Breaker). Potholes to either end of the Squeeze are water-filled and contain fish and yabbies.

Beyond the Back Breaker the cave is joint dominated, as narrow rifts with chockstones, but the flat planes and angular blocks show that most of the rock is essentially in place and has moved very little. There are a few small chambers, but they are of no significance. The cave terminates at Sandy Chamber, about 5 m below the surface. Both the floor and the roof of the chamber are essentially joint planes in the granite, dipping at 25° in direction 290° (mag). Most of the cave between the Back Breaker and Sandy Chamber has permanent pools. Sizeable potholes up to a metre across are found at the downstream end of Sandy Chamber.

Formation Of The Cave

The cave is formed by a stream working its way underground in an area of granite. The granite is extensively jointed, and the opening of joints, perhaps simply by pressure release at the surface, provided some access to water. Once a cave is formed, hydrostatic pressure during times of flood might further widen the joints, enabling yet more water to be carried underground. Furthermore, part of the granite was extensively weathered by chemical alteration along joints, so that it consisted of rounded and angular corestones separated by saprolite (weathered rock in place). In several parts of the cave, and especially near the Big Pothole, the saprolite can be observed, still preserved in the joints, in seams up to about 15 cm thick. Otherwise there is little indication of weathering, except for some spheroidal weathering, with single shells about 1 cm thick on rounded corners of joint blocks both on the ground surface and inside the cave.

As the stream eroded its bed and followed widened joints, it would erode the soft saprolite much more than the hard corestones, and so cut down its bed until more and more of the water was carried underground. Thus the cave has some sections that are very angular, dominated by little-modified joints; a few parts that are rounded by old sub-surface weathering; and some potholes and concave curved surfaces formed by abrasion by the underground stream.

This is the mode of origin of several other granite caves, such as Labertouche in Victoria, which is slightly bigger than Crombie's Cave (Ollier, 1965, 1984; Finlayson 1981), and several caves in Girraween National Park in Queensland (Finlayson, 1982). Commonly caves of this formation, especially if the corestones are rounded, appear to be little more than a jumble of boulders. Crombie's cave is distinctive in that the angular joint planes are very well preserved, partly because the pre-weathering was not as extensive as in Labertouche and some other caves, and partly because we are seeing an early stage in the development of a granite cave.

In discussing granite caves in Victoria, Finlayson (1981) suggested three possible relationships between the weathering and the erosion of the cave:

- The weathering and erosion may be almost contemporaneous, with the weathering just ahead of erosion.
- The weathering may be ancient.
- The alteration of the granite may be hydrothermal (created by hot water, probably related to igneous intrusion of the granite itself). In Crombie's Cave only situation (2) is plausible and deep weathering of granite is very well known and documented in the Armidale region. The weathering may well be of Mesozoic age, and is certainly older than 30 million year old basalt lava flows which in places overlie deeply weathered granite.

The other interesting feature of these caves is that the river has not only lowered its course by erosion of saprolite, but has actively worn down parts of its bed by active grinding (corrosion) and the formation of potholes. Evidently the stream did not find a course that ran

Plate 3. Multiple potholes, West entrance

continuously across saprolite, but occasionally crossed solid rock, and in these parts downcutting had to be by mechanical erosion. Such potholes are not common in the Victorian granite caves, though Finlayson (1981) recorded some bedload gravel and polished and scalloped boulders. Abrasion features are reported in Queensland where Finlayson (1982) recorded that *"The cave morphology clearly indicates that once the flow path is open, abrasion becomes the major process."* He described the River Cave as having *"water worn polish"* and Goebel's Cave has a *"bedrock floor pitted with scour holes which contain sand and gravel."* His photograph of Goebel's Cave shows potholes and scours similar to those of Crombie's Cave.

A stream needs a bedload of "tools" to erode its bed. Granite weathering itself provides sand and clay, and although sand can be effective in long term erosion it is not likely to form large potholes up to over a metre across like those found in Crombie's Cave. Sandy Chamber and potholes near the west entrance are floored by typical granite sand. The larger potholes contain pebbles of a variety of rock - sandstone, silcrete and chert - but not granite. It is perhaps important in the formation of this cave that the catchment, though small, contains a variety of hard rocks that can provide pebbles.

Cave formation was probably enhanced by the location of Powers Creek close to a steep gorge, which means that it was in a good position for vertical incision.

Life In The Cave

The cave is home to creatures that would usually live in the stream and are by no means remarkable. We observed yabbies, frogs and mosquito fish (*Gambusia affinis*), an exotic fish introduced from southeast U.S.A. but now widespread. Earlier visitors have recorded water spiders, lizards and frogs. The whole cave fills with water after heavy rain, so there are no bats.

Discovery

The cave was discovered in 1973 by Bob Crombie, a National Parks and Wildlife Ranger at Glen Innes, who noticed "a stream pouring out of a granite wall."

Caving

The cave can be traversed without equipment, but a rope is helpful at the entrances and at the Big Pothole. The Squeeze is an unpleasant tunnel leading to the Back Breaker, where a caver has to manoeuvre with body bent awkwardly through a narrow opening without slipping into a crevice. At least one girl has been stuck here and had to be rescued by pushing from below (standing chest deep in water) and pulling her legs from above (Smith, 1981).

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WIGLEY, T.M.L. and WOOD, I.D., 1967 Meteorology of the Nullarbor Plain Caves. In: J.R. DUNKLEY and T.M.L. WIGLEY (eds), Caves of the Nullarbor. A Review of Speleological Investigations in the Nullarbor Plain. Southern Austalia: 32-34. Speleological Research Council, Sydney.

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