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P.J. Ackroyd *Spinella buchanensis*

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  -report of the 1973 Niugini Speleological Research Expedition to the Muller Range.
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Radon and Its Decay Products in Caves

Craig M. Barnes, Julia M. James and Stewart Whittlestone

Abstract

Most trace radioactive substances in normal soils are solids that possess physical properties and decay half-lives that prevent them from being considered a natural radiation hazard. Radon, however, is a gas with a half-life just large enough for it to be able to diffuse out of the ground in which it is formed and migrate in open air from its origination point with changes in air flow. Whilst being solids, the decay products of radon are highly reactive and possess half-lives in the order of minutes. Consequently, the decay of these compounds, with the associated production of high energy α-particles, presents a possible health risk. Investigations into radon and its progeny in Australian caves are showing the presence within the caves of high levels of these substances. Described here are the factors that have been shown in studies worldwide to affect these levels over time within cave systems.

Introduction

Radon and its short-lived decay products are a major issue in human exposure to natural sources of radiation, especially with regard to enclosed spaces such as mines, buildings and caves. Indeed, over the last few decades, research has linked elevated levels of radon to the increased numbers of fatal cancers experienced by miners in some mines (Lorenz 1944; Jackson *et al.* 1987; Prime and O'Hara 1991), especially as the levels of radon in some abandoned mines have been measured as high as 240 million Bq m^{-3}. Unlike mines, the study of radon levels in caves has been limited. Nevertheless, it has been found that in many of the caves commonly used by the general public, such as the Carlsbad Caverns (Wilkening and Watkins 1976) in New Mexico, USA, and in wild caves, such as the Giants Hole (Bown 1992) in Derbyshire, UK, there are high levels of radon and radon decay products, the highest at present being 160,000 Bq m^{-3} in the latter wild cave.

Investigation into the levels of radon in Australian caves was initiated in 1991 (James 1996 pers. comm.). Test studies were required on the use and suitability of track etch detectors in measuring radon levels in buildings, and these tests were performed in the caves below the Nullarbor Plains. The incidental results of these tests, and of subsequent studies at other Australian cave systems, showed the existence of high levels of radon in these systems (Lyons 1992, Solomon *et al.* 1992).

The reasons for studying radon and its decay products in caves can be summarised as:

- determining whether there are health concerns with regard to the concentrations of radon and radon decay products for tourists and, more significantly, guides and maintenance workers;
- determining possible sources for any noticeably raised levels of radon;
- determining the distribution and flow of radon within the cave; and
- suggesting methods of reducing exposure to any levels of radon or radon decay products deemed to be dangerous to health in ways that do not harm the sensitive cave environments.

Background

The only naturally occurring heavy radioactive isotopes are uranium-235 (^{235}U), uranium-238 (^{238}U) and thorium (^{232}Th). These primordial constituents of all rocks and soils possess extremely long half-lives, the time elapsed since their creation being insufficient to facilitate the decay of these isotopes into other more stable compounds. The decay paths of these three elements is long and complex, proceeding through various shorter lived radioactive atoms until the formation of the stable non-radioactive lead isotopes (Figure 1). Because of their chemical reactivity, these intermediates tend to stay within the material in which they were formed. However, in each decay process, an isotope of the noble gas, radon, is formed. Radon (essentially inert in cave environments) can diffuse slowly through solid matter into the air (Hopke 1987), where it becomes a significant contributor to the background levels of natural radiation. Indeed, over 50% of background radiation is from radon decay.

Radon

The normal background level of radon in outdoor air is about 7 Bq m^{-3} [1]. Generally radon levels for enclosed spaces such as caves will be significantly higher than outdoor levels because dispersion of the gas by airflow changes is more restricted and thus less effective. Furthermore, the average air pressure differential experienced by caves often results in a pooling of gases within these spaces. Thus Radon levels found in caves can range from outdoor levels to several thousand Bq m^{-3} averaged over a year. For instance, levels at Wombeyan caves average 240 Bq m^{-3} annually whilst those at Jenolan (northside) caves are around 1500 Bq m^{-3} (Figure 2).

[1] The becquerel (Bq) is the SI unit for the measurement of radioactive decay, and is equal to one decay per second.

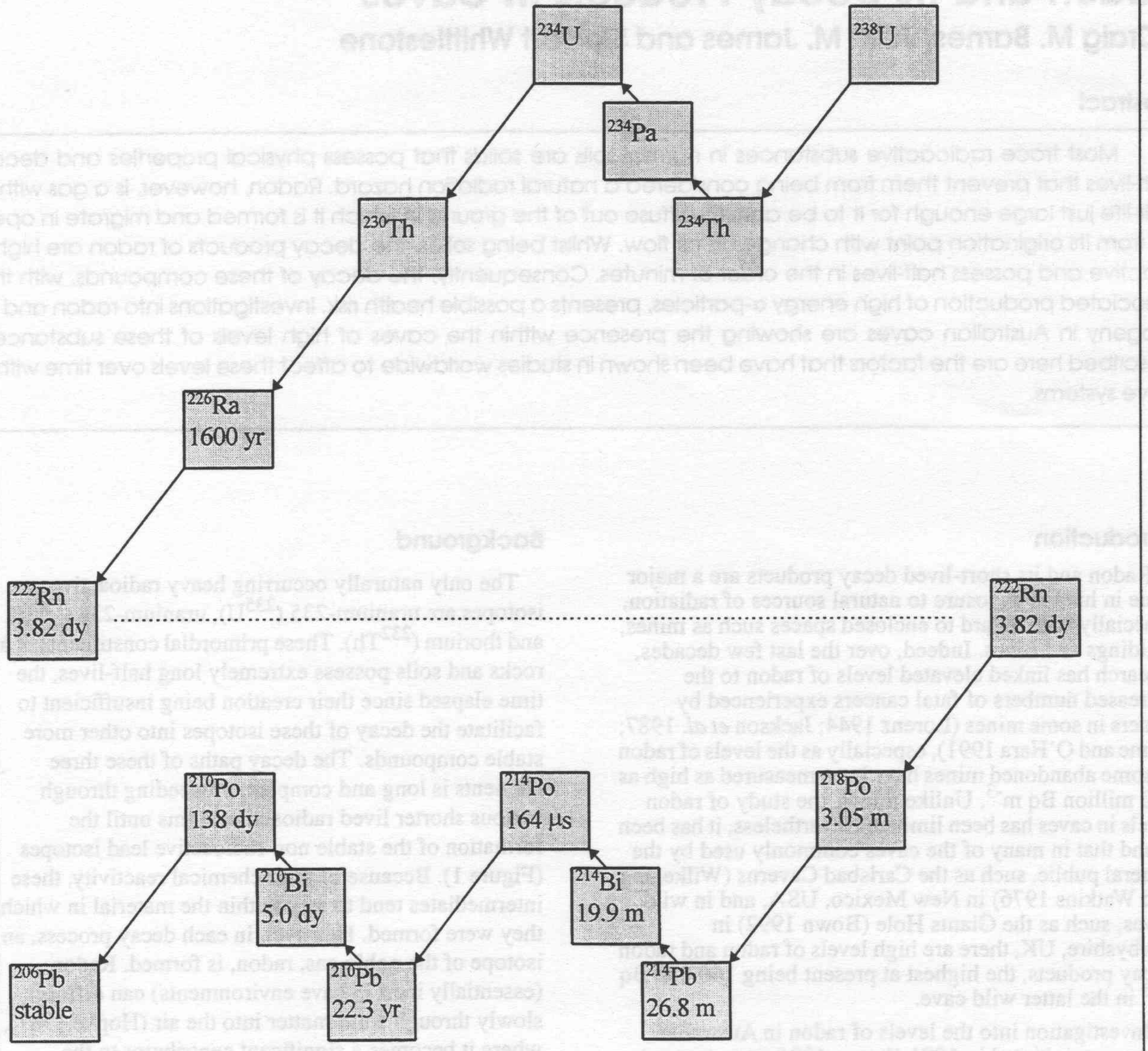

Figure 1. Decay chain and half-lives for the radon isotope, ^{222}Rn, and its decay products.
long downward arrow = α-decay short upward arrow = β-decay

The study of radon levels in caves began in the 1970's and, since 1974, radon levels have been monitored and analysed in both wild caves and show caves around the world. For example, radon levels have been measured in caves in Derbyshire, UK (Gunn *et al.* 1991a,b), New Mexico, USA (Wilkening and Watkins 1976), Australia (Solomon *et al.* 1996) and Budapest, Hungary (Géczy 1993). These measurements have shown radon to vary both seasonally and diurnally, with maximum levels observed in summer and during daylight hours, and minimum levels in winter and at night for most cave systems.

Radon Decay Products

The decay products (progeny) of radon are polonium-218 and -214 (^{218}Po, ^{214}Po), lead-214 (^{214}Pb) and bismuth-214 (^{214}Bi). Lead-210 (^{210}Pb), with a half-life of 22 years, is considered to be stable and, therefore, the end point for the progeny decay sub-chain (Figure 1). The chemistry of the radon progeny is of some importance. While both lead and bismuth are relatively unreactive, polonium isotopes are both reactive and extremely toxic. Consequently, high levels of these could be harmful in and of themselves, without the added danger of their being radioactive. However, the radiation hazard predominates.

All of the radon decay products are solids, and so can "plate out" of the air onto other surfaces, such as those provided by the walls of caves, dust particles, moisture droplets and condensation nuclei. Condensation nuclei are small airborne particles formed by photochemical or combustion processes in the outside atmosphere that have been transported into the cave atmosphere through air exchange. Because of the small size (< 1 micron diameter) and high relative abundance of, and thus the large surface area provided by, condensation nuclei, radon decay products are more likely to attach to these particles rather than dust or water droplets. Therefore, the radon decay products are a mixture of "attached" and "unattached" particles.

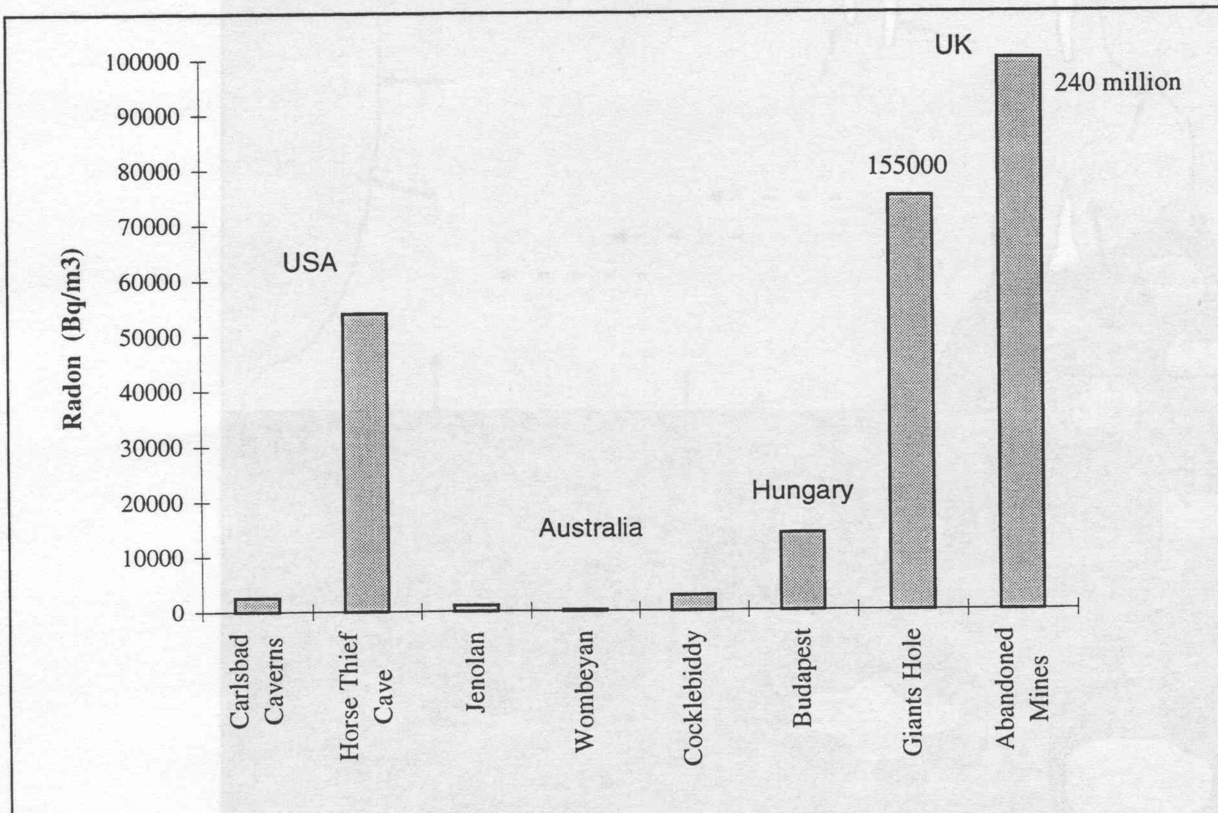

Figure 2. Radon levels in caves and mines.

For a chain of radioactive isotopes where the parent is relatively long-lived, the amount of each chain member will adjust until the sources and losses of each are in balance. When the only source is an original amount of the parent and the only losses are decay processes, the equilibrium reached is one where the activities of the parent and its decay products are equal. That is, they are said to be in secular equilibrium. For the radon decay chain, in the absence of external influences, it takes approximately 4 hours for this state to be achieved (Robkin 1987). Processes, such as plate-out onto walls or those that cause changes in airflow, which operate within this time frame and which alter the abundance of the particles by introducing or removing them, can lead to departure from this "ideal" state.

The earliest research concerning radon decay products in caves was undertaken during the late 1970's in the Carlsbad Caverns, New Mexico, USA (Ahlstrand 1980). These studies showed that there existed temporal variations in the levels of radon decay products and that these levels were probably related to seasonal, diurnal and pressure related phenomena. A subsequent study of the decay product levels within Giants Hole, Derbyshire, UK (Middleton *et al.* 1991), found that changes in the radon decay product levels were primarily the result of changes in the direction of airflow within the cave and that this in turn was related on a seasonal and diurnal scale to temporal variations in the temperature gradient between the cave and external air.

Factors Affecting the Levels of Radon and Radon Decay Products in Caves

Radon and radon decay product levels in cave atmospheres are dependent upon the whereabouts of the parent (radium) source, the emanation of radon from the ground, and the rate of introduction and removal of radon in air and water (Prime and O'Hara 1991; Lyons 1992; Nazaroff 1992; Blaauboer and Smetsers 1996) (Figure 3). The probability of a radon atom escaping into the air varies with distance from the surface of the rock and the geology. As the surface is approached, this will increase, as release of radon into larger air cavities like caves becomes important. The geology and physical processes such as weathering help determine the 'porosity' of the earth, and thus to some extent the moisture content and permeability of the soils. Consequently, levels of radon in caves is controlled by the radium concentration in the cave structure, the physical structure of the cave walls which affects the diffusion rate, and by atmospheric pressure changes.

Water can also be an important source of radon in caves, depending on the rock over (or through) which it has flowed (Prime *et al.* 1991) before entering the cave. Water flowing over or through rock of high uranium or radium concentration often has high radon levels. Despite the low solubility of radon in water, the high concentrations of radon found in most soils readily forces some radon into groundwater and circulating subsurface

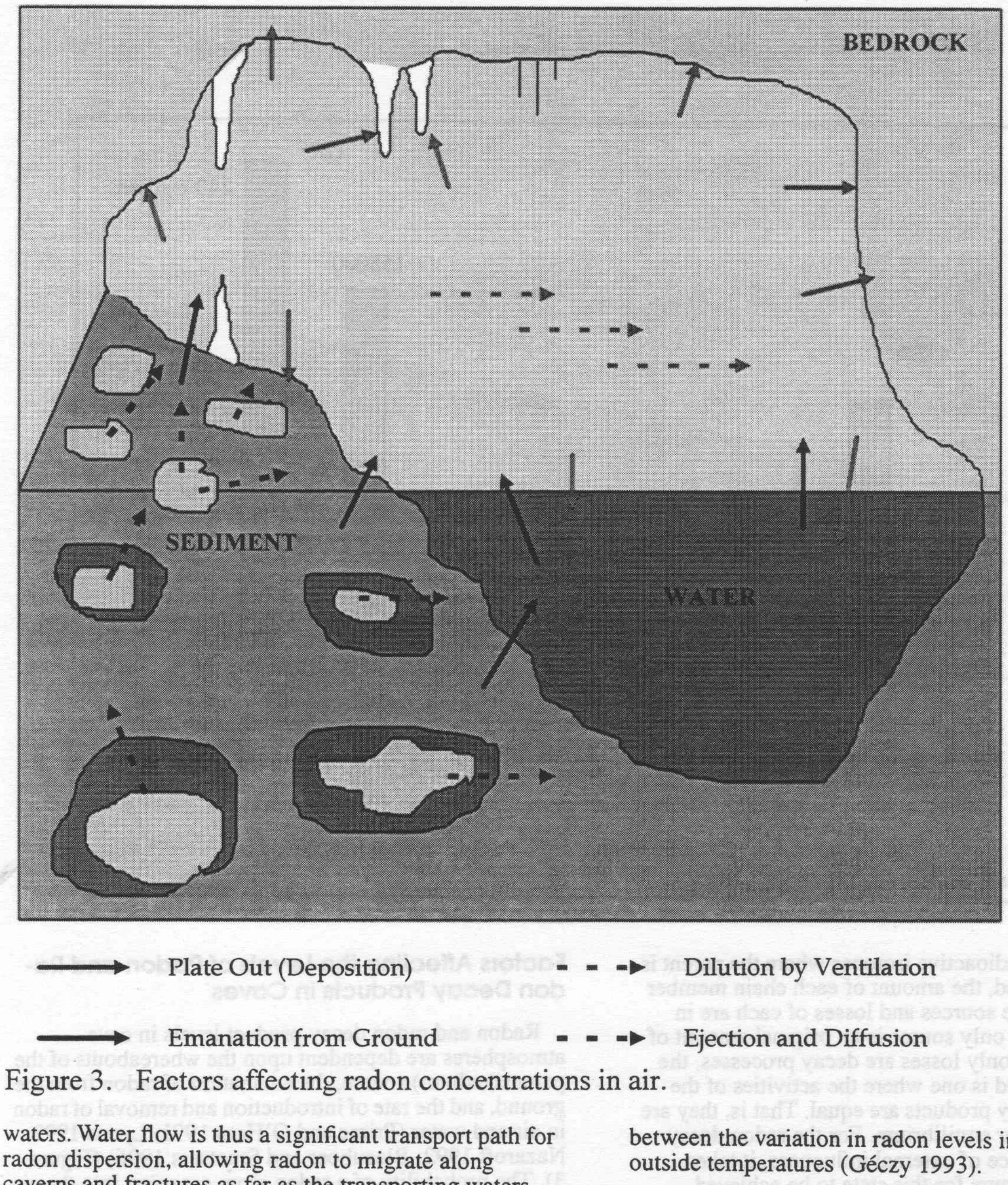

Figure 3. Factors affecting radon concentrations in air.

waters. Water flow is thus a significant transport path for radon dispersion, allowing radon to migrate along caverns and fractures as far as the transporting waters allow (Nazaroff 1992; Hakl *et al.* 1993a), and leading to possible increases in radon levels at sites removed from the point of origin of the radon

Exchange rates between cave and external air can be complicated, and are dependent upon temperature differences between the cave and outside and the cave configuration (entrance above or below the limestone voids, mazes, complex passages, chimneys etc.). For example, outside caves, a temperature inversion can occur some metres above the ground at night, resulting in an increased radon concentration at ground level. During the day, the air heats more uniformly and so mixes more thoroughly. Wind direction can also be important to cave airflow as can be the presence of active streamlets. Indeed, any factor likely to change airflow patterns within a cave is also likely to alter the levels of radon and its decay products.

Middleton *et al.* (1991) and Prime and O'Hara (1991) confirmed that the direction of airflow is one of the dominant factors affecting both the spatial and temporal distribution of radon decay products within caves. On both a seasonal and diurnal scale, airflow direction is determined by the temperature gradient that exists between the cave and external air. Some of the temporal variations have been related to changes in atmospheric pressure. However, strong correlations have been found between the variation in radon levels in the caves and outside temperatures (Géczy 1993).

Exposure to ^{222}Rn & its Decay products

Knowledge of the health effects of radon and its decay products is derived mainly from studies of cancers in underground miners, all of which have unambiguously shown that prolonged exposure to high concentrations of these substances leads to a high number of fatal lung cancers (Behounek 1970; Jackson *et al.* 1987; Eisenbud 1987). However, extrapolation of these results to situations where humans are exposed to much lower radon levels, for example, in caves, has severe limitations despite being of prime interest with respect to general public health.

Being a gas ^{222}Rn can be inhaled, although it is generally exhaled again before decay can occur. Radon is also somewhat soluble in blood and body fat (Eisenbud 1987). However, should radon decay within the body, it will not only emit an α-particle but deposit radon progeny as well, whereupon a further two α-particles will be emitted, also within the body.

Radon first decays to ^{218}Po. Polonium-218 is a chemically active solid material that can bind to lung tissues, and which has a half-life of about 3 minutes. It too decays by emitting an α-particle, to ^{214}Pb. Lead-214 quickly decays through harmless β-emission into ^{214}Po, which emits a further α-particle upon decay into the stable nuclide ^{210}Pb.

Even when produced outside the respiratory tract, radon progeny can be inhaled. Indeed the amount of radon progeny deposited as a result of radon decay within the body is negligible compared to the amounts of progeny that are inhaled. These solids can become attached to condensation nuclei and other airborne particles or remain unattached, thus altering the overall size of the particle. If inhaled only a small fraction of those radon decay products breathed in will be exhaled again, with the particles becoming trapped some distance along the respiratory tract in inverse correlation to the size of the particle.

Robkin (1987), claims that the unattached fraction, because of their extreme reactivity, deposit in the respiratory tract with 100% efficiency. However, the slightly lower reactivity and velocities of the attached fraction mean that they can travel further along the respiratory tract before plating out. Because of this, the attached fraction pose a greater danger to health than the unattached fraction. Regardless of this small distinction, the decay of the progeny isotopes produces high energy α-particles which, if the nuclides are trapped in the lungs, can damage the sensitive lung tissue

The properties of α-particles are such that they are only a health hazard if the emitter is in contact with living tissue. The relatively large, positively charged α-particles rapidly lose their energy to surrounding atoms. This means that they do not penetrate the skin and are stopped by a few centimetres of air. However, if the α-emitter is in the body (*e.g.* on the lung tissue), all of the energy is released to a much more sensitive tissue.

The chances of the energy released by α-particles breaking chemical bonds within organic molecules or causing ionisation or forming reactive free radicals are relatively high. All of these changes have the potential to disrupt the normal metabolism and produce changes which may either be easily reversed or affect cell replication, cause cell death, or in a limited number of cases, induce cancerous or abnormal growth. As those α-particles released by the radon decay products are more energetic than those emitted during radon decay, the progeny are once more revealed as being of greater concern to public health.

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Abstract

A History of Croesus Cave

----------*Rod How and Michael Lichon*

Croesus Cave, by the Mersey River at Liena, Mole Creek, Tasmania, was discovered around 1896 by surveyors searching for a rail route to the west coast. The first caver group to explore it was the Tasmanian Caverneering Club in 1947. By 1963, the upper entrances and most of the cave were explored. Until the discovery of Kubla Khan, it was regarded as Tasmania's finest cave. Photography began with a 1952 trip by Sydney cavers. Local Reg How and Herb King photographed the cave over many trips 1959-64 using modified kerosene Tilley lamps. Exploration involved using three sets of clothes, a spar & drum raft at the Master Lock, and ladders to climb the flowstone banks. A trench was later dug at the entrance to lower the water level.

Following vandalism, the main entrance was gated in 1958. On 24th August 1970, a flood from 228 mm rain + indeterminate snowmelt in 48 hours ruptured the gate construction. The gate was soon replaced and 2 years later a State Reserve was declared to cover this entrance and that of Lynd's Cave. Vandalism continued, with items being sold at markets. The cave was then subject to Restricted Access in 1986. Adherence to permit conditions & reporting has been lax. Vandalism continued. In 1989, Mole Creek Caving Club mounted a trip to clean mud off the Snowbank. Gates were finally placed on the upper entrances in 1990. In 1992, stringlines were placed to define no-go areas, and a rubber raft was installed to divert impact from the Golden Stairs. Information sheets are now issued with permits. While the cave has been saved from tourist cave development so far, publicity still draws attention to the cave.

Logging in the catchment commenced in the 1940's and lasted several years. Water chemistry suggests the famous gours are being dissolved as a result of the catchments logging. Road construction during the Mersey-Forth Hydro development passed over the cave, along with a gravel quarry. This has been suggested as cause for some recent muddying and roof failures. In 1990 a Forestry management review concluded the surface catchment should be reserved from logging and other disturbances. The Conservative Tasmanian Government refuses to reserve the catchment despite the management review and the compelling evidence regarding surface use and cave impacts.

Full paper to appear in Illuminations 3, *in press*.

Review

The Caves of Thailand
Thailand Caves Catalogue
Caves of North-West Thailand

Publisher: Speleological Research Council
Reviewer: Bill Mixon

The Caves of Thailand. John R. Dunkley. 1995 124 pp. *Thailand Caves Catalogue*. John R. Dunkley. 1994. 44 pp. *Caves of North-West Thailand*. John R. Dunkley. and John B. Brush, eds. 1986. 62 pp. All A4 size softbound. Available from the SRC Ltd, PO Box 183, Broadway, NSW 2007, Australia.

The Caves of Thailand is a summary of recorded information on over two thousand caves in the country, but many of the entries gleaned from miscellaneous literature give very little information. Thailand has only scattered areas of limestone, but a number of fairly long limestone caves have been explored, including the 12,600 m long main section of the Mae Lana system. Thailand is a heavily Buddhist country and many caves are known primarily for their cave temples or archaeological remains. There are also sea caves. Cave maps are limited to a couple of pages of very small-scale line maps. There are introductory chapters on the geology and the cultural significance of the caves of Thailand, and the bibliography contains over two hundred references.

The 1994 catalogue is a much condensed version of the 1995 volume, with a limited bibliography of only a couple dozen items and the cave information reduced to one line per cave.

The *1986 Caves of North-West Thailand* is a report on several expeditions by the Australian cavers during the middle eighties to Thailand, especially the Nam Khong area in the far northwestern corner of the country. They explored and mapped 25 kilometres of cave, including those that are still the longest mapped caves in the country. The volume contains real maps of the caves they visited.

The Caves of Thailand is the reference on the caves of that tropical country. There would be little point in also buying the 1994 catalogue. *Caves of North-West Thailand* will be more interesting to those wondering what caves and caving in Thailand are really like.

Naked Fame Tests for, and Human Tolerance to, Foul Air in Caves

. . . . Garry K. Smith

Abstract

The paper examines the reliability of the "Naked Flame Test" for measuring the concentration of carbon dioxide (CO_2) in caves. It reviews the ways in which carbon dioxide gets into caves, how it forms pockets of high concentration and the composition of the atmospheres in these pockets. A cave air index is used to generate theoretical tables of cave atmosphere compositions for two scenarios composed of carbon dioxide from differing sources. Conditions for combustion together with levels of carbon dioxide and oxygen (O_2) required to extinguish flames are stated. The fuel components of various combustible materials available for the Naked Flame Test are described. The paper presents and discusses the results of the laboratory tests on matches, candles and butane cigarette lighter in reduced oxygen atmospheres. It reviews the physiological effects of low O_2 and high CO_2. It is concluded that the Naked Flame Test measures O_2 concentrations and is unreliable for measuring CO_2concentrations. Elevated CO_2 levels are recognised as being the life threatening component of most cave atmospheres, however, it is also concluded that the Naked Flame Test is still the safest way for an inexperience caver to test for hazardous cave atmospheres.

Cavers are quiet aware that if they are breathing heavily, have a headache or feel tired and lethargic, there may be a high concentration of carbon dioxide (CO_2), or "foul air" in the cave atmosphere. For those without sophisticated instruments, a simple "Naked Flame Test" is often done to confirm this suspicion. This "Rule of Thumb" method of measuring the approximate percentage of CO_2 in caves has been used for many years. This raises a number of questions.

They include:

- Are CO_2 concentrations or low oxygen (O_2) concentration in the cave being measured when a naked flame is extinguished?
- How reliable is the Naked Flame Test for measuring CO_2 concentrations?
- Should low oxygen concentrations be considered as the life threatening component of the cave atmosphere instead of elevated CO_2 concentrations?
- Can butane fuelled cigarette lighters (eg. common disposable gas type) be added to the list below?

A simple naked flame methods of testing for CO_2 uses the following flames as indicators of CO_2 concentration (Australian Caver 1990).

1% CO_2	a lighted match will go out
4% CO_2	a lighted candle will go out
6% CO_2	a carbide lamp will go out

To answer the question of how reliable are these tests, it is necessary to examine CO_2 and O_2 concentrations required to support combustion of various materials. To find out what is the most life threatening situation (low O_2 or high CO_2), it is necessary to examine the concentrations of these gases which are harmful to humans.

How CO_2 gets into caves and forms pockets of high concentration

As discussed in more detail in the article "Caves, Carbon Dioxide & You", (Smith 1993), CO_2 is produced in the cave in two major ways.

In the first, **Scenario 1**, CO_2 is absorbed by the ground water as it passes through surface soil containing high concentrations of the gas, due to the decay of vegetation. This water percolates through the rock strata, enters the cave system, and degasses its CO_2 usually taking part in the calcite deposition cycle. In this instance the addition of extra CO_2 to the cave atmosphere displaces O_2 and nitrogen (N_2). See Table 3.

Under specific conditions, soil CO_2 concentrations can reach as high as 12%, however most values range between 0.15% and 0.65%. Therefore the 24% value listed at the bottom of Table 3 is unrealistic. It is shown as an example of what concentration is required to reduce the cave atmosphere oxygen concentration to a level which will not support combustion.

Halbert (1982), relates this "Foul Air Type 1" cave atmosphere to the introduction of CO_2 into the cave atmosphere and all other components are diluted - the source of the CO_2 is immaterial. An atmosphere resulting from purely a type 1 process occurs quite slowly and it requires five percent CO_2 to reduce the O_2 level by one percent.

In the second, **Scenario 2**, the CO_2 is a product of organic decomposition by micro-organism metabolic processes and respiration by fauna such as bats or humans. In this instance the oxygen concentration is reduced in proportion to the increase in CO_2. See Table 4.

Halbert (1982) "Foul Air Type 2" describes in great detail the relationship between consumption of O_2, and production of CO_2 in the metabolic process of living organisms. Essentially the volume ratio of CO_2 produced to O_2 consumed, called the "respiratory quotient" (RQ) is not constant and can vary between 0.7 and 1, depending on organic matter involved. i.e. carbohydrates, fats or protein. If fats were utilised solely in the metabolic process the RQ = 0.7, and would result in a consumption of O_2 with a relatively smaller amount of CO_2 volume being produced.

In the third, **Scenario 3**, "Foul Air Type 3", cave atmosphere which has resulted from the introduction of other gasses, such as methane and nitrogen and the non-respiratory uptake of O_2 as well as CO_2 stripping by water. Another example is "stink damp" so named because it often contains hydrogen sulfide and the O_2 is significantly more depleted than in "Type 2". Foul air consisting strictly of "Type 3" is rare in Australian caves, although some samples collected at Bungonia do suggest a few caves contain atmospheres influenced by this mechanism.

Also falling into Halbert's (1982) "Foul Air Type 3", is an atmosphere which has resulted from a combination of scenarios 1&2 with addition of another mechanism which alters the gas concentrations. In general cave atmospheres with a mixture of Type (3+1) or (3+2) are classed as a "Foul Air Type 3".

The CO_2 to O_2 relationship in caves has been discussed in more detail by Halbert (1982) and Osborne (1981).

The two major gases in the atmosphere are oxygen and nitrogen. Table 1 shows the density, molecular weight and % in a normal atmosphere for these gases and carbon dioxide. At a given temperature, a volume of CO_2 is 1.57 times heavier than the same volume of N_2 (43.99/28.01 molecular weight ratio) and CO_2 is 1.38 times heavier than the same volume of O_2 (43.99/31.98 molecular weight ratio).

Gas	Density 25 °C $g L^{-1}$ at 1 atm	Molecular weight	% in normal atmosphere
CO_2	1.931	43.99	0.03
O_2	1.404	31.98	21
N_2	1.229	28.01	78
Rare Gases			0.97

Table 1. Statistics of gases

Properties of Carbon Dioxide

Even though CO_2 is 1.57 times heavier than nitrogen and 1.38 times heavier than O_2, it will have a tendency to disperse in an isolated volume of air, due to molecular diffusion. In other words, a mixture of gases will not separate into layers of various density gases if they are left for a long time in a still chamber. On the other hand various gases purged separately into a closed container will become uniformly mixed over a period of time. A possible explanation of the high concentrations of CO_2 in caves with relatively still atmospheres, is that CO_2 is being produced metabolically or entering the cave via ground water at a greater rate than the gas can diffuse into the cave atmosphere. This would explain why foul air, with a high CO_2 concentration is found in pockets at the lower sections of a cave. Frequently there appears to be a definite boundary between good air and foul air. This would indicate that dispersion of the CO_2 was occurring at a relatively slow rate compared to the gas production. These atmospheres can be attributed to 'Foul Air Types' 1 or 2, or a combination of both, however the CO_2 is being introduced into a relatively still cave atmosphere and molecular diffusion is not sufficient to disperse the gas with an even gradient over the vertical range of the cave.

Another possible scenario in caves with relatively still atmospheres, is that CO_2 is being produced faster than it can diffuse into the rest of the cave atmosphere (by molecular diffusion) and it sinks to the lowest point in the cave thus building up in concentration.

It should be noted that foul air will not build up in caves with two entrances at different elevations, as temperature gradients cause air flows which flush the cave atmosphere. Long branch passage in these caves may not be cleared of foul air by air movement between entrances.

Carbon dioxide is "regarded as a `hot gas' due to its low thermal conductivity, heat is not conducted away as rapidly as in normal air, so a person standing in it feels warm about his lower limbs" (Strang, 1990).

Calculation of Gas Concentrations in a Cave Atmosphere

In dry air, the total pressure of a mixture of gases is equal to the sum of their partial pressures.

The atmospheric or barometric pressure of dry air $= pN_2 + pO_2 + pRG + pCO_2$ (RG = Rare Gases)

However since most cave atmospheres have high humidity, a water vapour (H_2O) component should be included in the equation.

Barometric pressure $= pN_2 + pO_2 + pRG + pCO_2 + pH_2O$.

Water vapour constitutes about 0.5% by volume of a saturated cave atmosphere at 20 °C and is 0% in a dry atmosphere. Halbert (1982) uses the Cave Air Index (CAI) to characterise gas mixtures found in caves on a dry atmosphere basis. The water vapour component in the calculation, slightly changed the concentrations of CO_2 and O_2, but did not affect the arguments derived from his data. For simplicity, cave atmospheres may be considered to consist of O_2, CO_2, and a residual fraction (RF) composed of rare gases, N_2 and water vapour.

$$\text{Cave Air Index} = \frac{CO_2 \text{ concentration}}{21 - O_2 \text{ concentration}}$$

Table 2 shows the relationship between possible mixes of the scenarios described in this paper, Foul Air Type and CAI.

Foul Air Type *(after Halbert 1982)*	Possible Mixes	Cave Air Index
1		$4 \leq CAI \geq 5$
1 + 2 combination	1 + 3	$1 \leq CAI < 4$
2	2+1, 2+3, 1+3	$0.75 \leq CAI < 1$
2 + 3 combination	1+3	$0 < CAI < 0.75$
3	-	$CAI = 0$

Table 2. Possible mixes of cave air scenarios and correlation with Halbert's "Foul Air Type" & Cave Air Index.

The "Foul Air Type 3", where CAI = 0, is rare in caves. In general cave atmospheres with CAI of < 0.75 are regarded as falling into the Foul Air Type 3. Halbert (1982) gives the example of "Foul Air Type 3" atmospheres containing 1% CO_2, 17% O_2, and 82% RF and another with 4.5% CO_2, 10.5% O_2, and 85% RF. He points out that a low absolute O_2 concentration does not need to be present. However in practice "Foul Air Type 3" atmospheres likely to be encountered in caves will have low O_2. In addition this type of foul air may have deceptively low CO_2. Some readings at Bungonia suggest a "Foul Type 3". They include atmospheres in Grill Cave with a composition of 1.4% CO_2, 12.0% O_2, 86.6% RF which gives a CAI of 0.16 and readings in Odyssey Cave of 2.8% CO_2, 14.5% O_2, 80.3% RF which gives a CAI of 0.43. (Halbert 1982).

The following tables 3, and 4 illustrate the changes in oxygen and residual fraction for atmospheres with elevated carbon dioxide sources as in scenarios 1 and 2.

CO_2%	O_2%	RF%
1	20.75	78.25
2	20.50	77.50
3	20.25	76.75
4	20.00	76.00
5	19.75	75.25
6	19.50	74.50
8	19	73.00
10	18.50	71.50
12	18	70.00
24	15.00	61.00

Table 3. Calculations of major gas concentrations in a cave atmosphere using scenario 1 with a CAI of 4

CO_2%	O_2%	N_2%
1	20	79
2	19	79
3	18	79
4	17	79
5	16	79
6	15	79
8	13	79
10	11	79
13	8	79

Table 4. Calculations of major gas concentrations in a cave atmosphere using scenario 2 with a CAI of 1, i.e. RQ = 1

Conditions Required for Combustion

Before combustion can occur, three conditions must be satisfied.

1. There must be a fuel or substance which can be burnt.
2. The fuel must be heated to its ignition temperature. That is the lowest temperature at which combustion can begin and continue.
3. There must be enough oxygen to sustain combustion, either in the surrounding air or present in the fuel.

Levels of CO_2 and O_2 required to extinguish flames

When fighting a fire, the aim is to dilute O_2 to a concentration which will not support combustion and this is the main flame extinguishing mechanism of CO_2. The same effect can be obtained by adding an inert gas such as nitrogen, argon, neon or helium, to an atmosphere at about 17% concentration by volume. By the addition of these gases O_2 can be diluted to a life threatening level. (Safe Handling of Compressed Gases 1992).

The Le Chatelier's principle states that *"any system in equilibrium shifts the equilibrium, when subjected to any constraint, in the direction which tends to nullify the effect of the constraint"*. Using butane (cigarette lighter fuel) as an example, then:

butane + oxygen → carbon dioxide + water

$$2C_4H_{10} + 13O_2 \rightarrow 8CO_2 + 10H_2O$$

Simply this means that if the CO_2 concentration is raised and/or the O_2 concentration is reduced, then the reaction will slow down and eventually stop. Increasing the CO_2 concentration will have a smaller effect than the decreasing the O_2 concentration. The experimental data in this paper and that of Kuchta (1985), indicate that a 1% increase in CO_2 concentration will raise the O_2 concentration required to support combustion of a given substance by less than 0.05% O_2.

In the majority of cave atmospheres, it is the low concentration of O_2 which stops combustion, not the high concentration of CO_2.

Vapour	CO_2 to air	O_2 %	N_2 %	CO_2 %	Rare Gas %
Carbon disulfide	1.59	8.11	30.12	61.40	0.37
Hydrogen	1.54	8.27	30.71	60.64	0.38
Ethylene	0.68	12.50	46.43	40.49	0.58
Ethylether	0.51	13.91	51.66	33.79	0.64
Ethanol	0.48	14.19	52.7	32.45	0.66
Propane	0.41	14.89	55.32	29.1	0.69
Acetone	0.41	14.90	55.32	29.1	0.69
n-Hexane	0.40	15.0	55.71	28.6	0.69
Benzene	0.40	15.0	55.71	28.6	0.69
Methane	0.33	15.79	58.65	24.83	0.73

Table 5. Minimum volume ratios of CO_2 to air (column 2)which are required to prevent burning of various vapours at 25 °C (column 1)andthe composition of the resulting atmosphere resulting from addition of CO_2 (columns 3 to 6).(After Friedman. R., 1989. Data calculated from tabulations by Kuchta (1985)).

To calculate the final volume percentages of each gas from the (volume ratio) of CO_2 added to air.

$R + V = Y$

Where R = Volume of CO_2 required to give CO_2/ air volume ratio. (from table No.6)

V = Volume of air which CO_2 added to (= 1)

Y = Total volume of gases in CO_2 air mixtures

To find the percentage of gases in the new atmosphere (which will not support combustion of the various vapours because the O_2 has been diluted). The known percentage of gases in normal air are used. i.e. O_2 = 21%, N_2 = 78%, CO_2 = 0.03% and rare gases = 0.97%. It should be noted that R must be added to air CO_2 of 0.03%.

Gas% (fire retarding atmosphere) = Gas% (in normal air) / Y

Example.

*To calculate the O_2% in an atmosphere which **will not** support combustion of propane vapour, CO_2/ air ratio is 0.41 (Table 5)*

Therefore Y = 0.41+ 1

Y = 1.41

O_2% = 21/1.41 = 14.89 in new atmosphere.

From Table 5, it can be seen that the addition of CO_2, to dilute the O_2 concentration, will result in a CO_2 rich atmosphere which will not support human life (see Table 8). For this purpose much higher concentrations of CO_2 are present, than would be found in the majority of caves.

Nitrogen can also be used to dilute the O_2 concentration. However, since N_2 is less dense than CO_2 a comparison of Table 5 and Table 6 shows that almost twice the volume of N_2 is required to extinguish flames from the same fuel.

Vapour	N_2 to air ratio	O_2 %	N_2 %	CO_2 %	Rare Gas %
Carbon disulfide	3.0	5.2	94.5	0.0075	0.423
Hydrogen	3.1	5.1	97	0.0073	0.237
Ethylene	1.00	10.5	89	0.015	0.485
Ethylether	0.97	10.66	88.83	0.015	0.492
Ethanol	0.86	11.3	88.17	0.016	0.522
Propane	0.78	11.8	87.64	0.0169	0.545
Acetone	0.75	12.0	87.43	0.017	0.554
n-Hexane	0.72	12.2	87.21	0.0174	0.564
Benzene	0.82	11.54	87.91	0.0165	0.533
Methane	0.63	12.9	86.5	0.0184	0.595

Table 6. Minimum volume ratios of N_2 to air (column 2) which are required to prevent burning of various vapours at 25°C (column 1) and composition of the resulting atmosphere resulting from the addition of N_2 (columns 3 to 6). (After Friedman. R., 1989. Data calculated from tabulations by Kuchta (1985)).

Flame sources used for the Naked Flame Test Matches

There are two main types of matches, "Strike-anywhere" and "Safety". This paper will only deal with "Safety" matches as they are the only type readily available in Australia. In general, "Safety" matches can only be lit by striking them across a special surface on the side of their box or packet. The head is made of a mixture containing potassium chlorate, sulfur and other components, which will ignite at a temperature of approximately 182 °C. The coating on the box is made of amorphous phosphorus and sand.

Wooden "Safety" matches are generally made of poplar wood, which is dried to reduce moisture content to below 7%, then the "splint" is treated with an anti-afterglow solution (*retardant*) which prevents embers from forming after a flame is blown out. The second stage in production is dipping approximately 10 mm of the tip end into paraffin. This provides a base to carry the flame from the head to the wood. Then the tip (sometimes called a bulb) is added. Some match manufacturers add a final chemical coating that protects the match from moisture in air.

When a match is scraped across the box striking surface, it begins a chemical reaction between the potassium chlorate and amorphous phosphorus which in turn ignites the sulfur component of the head. The heat generated in the head vaporises the paraffin coating on the splint and the flame is drawn down from the head. Moisture is driven out of the timber, the retardant is burnt off, allowing the wood volatilise to vaporise and ignite. The head will fizz and not burst into full flame when there is a lack of O_2 in the atmosphere, as it's partial burn is due to the O_2 in the potassium chlorate contained in the head.

Book matches are a type of "Safety" match made of heavy paper (called *paperboard*) and the row or rows (called *combs*) of matches are bound into a paperback cover. The paperboard is also treated with an anti-afterglow solution and paraffin as with wooden matches (The World Book Encyclopedia 1992).

Candles

A candle burning in an area without draught will produce a steady flame. The flame's heat vaporises just enough candle wax to keep the flame burning at the same height. This is influenced by the length and type of wick and the type of wax. The wick serves as a place for the flame to form. When lit by another heat source, the heat from the burning wick melts the wax at its base and the liquid is drawn up the wick to the flame by capillary action. The heat in the flame vaporises the molten wax which then burns. Most candles today consist of beeswax or paraffin. The latter being the most common.

Paraffin is a wax obtained from petroleum and is a mixture of hydrocarbons which melt between 32 to 66 °C and vaporises at between 150 and 300 °C

Cigarette Lighter (Butane type)

Butane is a colourless, flammable gas which can be readily kept in a liquid state while under pressure at ordinary temperatures. Once the pressure in the lighter reservoir drops below 265 kPa at 25 °C, the liquid butane begins to vaporise until the pressure increases to an equilibrium point and further vaporisation ceases. When the lighter is operated, gas from the reservoir is liberated through a fine jet and a hot spark from the flint easily ignites the gas. Ignition temperature of butane can vary between 482 and 538 °C, however the hot flint spark is sufficient to begin combustion of the gas. At atmospheric pressure the normal vaporisation point of butane is -0.5 °C.

Butane lighters in O_2 deficient air

A cigarette lighter when lit in an atmosphere which will support combustion of butane will burn with the flame extending directly from the jet. When this lit cigarette lighter is slowly lowered into an atmosphere that will not support combustion (lower O_2, higher CO_2 concentration), an interesting phenomenon occurs. The flame will magically stay burning where the atmosphere will support combustion, just above the interface between the high and low O_2 concentrations, while the lighter is several centimetres below this interface.

In the CO_2 Pit of Gaden Cave, Wellington, New South Wales, Micheal Lake demonstrated the above phenomenon. When a lit butane lighter was gradually lowered into Pit, the 25 mm high flame stayed burning just above the oxygen deficient interface. The lighter body continued to be lowered until the 25 mm flame remained burning some 75 mm away from the lighter, in other words, the base of the 25 mm flame was 75 mm away from the cigarette lighter jet. Clearly at this depth in the pit the O_2 was now insufficient to support the combustion of butane as it issued from the lighter but 75 mm higher there was sufficient oxygen. This phenomenon can not occur with solid fuels, such as matches and candles, as the heat from the flame is required to vaporise the volatiles which then burn. When lowered further into the CO_2 Pit the butane lighter flame was totally extinguished.

A cigarette lighter which does not have adjustment for the flame can also be used to some degree to check for low O_2 concentrations. A subtle change in the flame height occurs as the O_2 concentration decreases - it becomes longer as the O_2 concentration decreases. This test is environmentally more desirable than the matches or candle method as unpleasant odours are not produced. However this method is not recommended for the novice as it requires some experience for reliable interpretation of O_2 concentration.

Laboratory Combustion Tests

To verify the O_2 concentrations required to support the flames of matches, candles and cigarette lighters, a series of tests were conducted in a controlled atmosphere chamber. A large inflatable glove chamber made of clear plastic was filled with normal air. The "Glove Bag™" Model X-37-27, was pre-loaded with all the components required for the experiment, then sealed from the outside atmosphere. A stand was used to hold a burning candle and another stand held a mini video camera (ELMO 120 with 15 mm lens). The chamber full of normal air, was then purged with argon to reduce the O_2 concentration. The O_2 concentration (as % by volume) was measured using a Teledyne Portable Oxygen Analyser, (Model 320). A small bleed line, vented excess hot air and fumes from the chamber as the argon gas reduced the O_2 concentration. At each 0.5% drop in O_2 concentration, four separate matches ("Kangaroo" brand) were lit and a video recording made of their burning. The lowest O_2 concentration reached in the chamber was 7.5%.

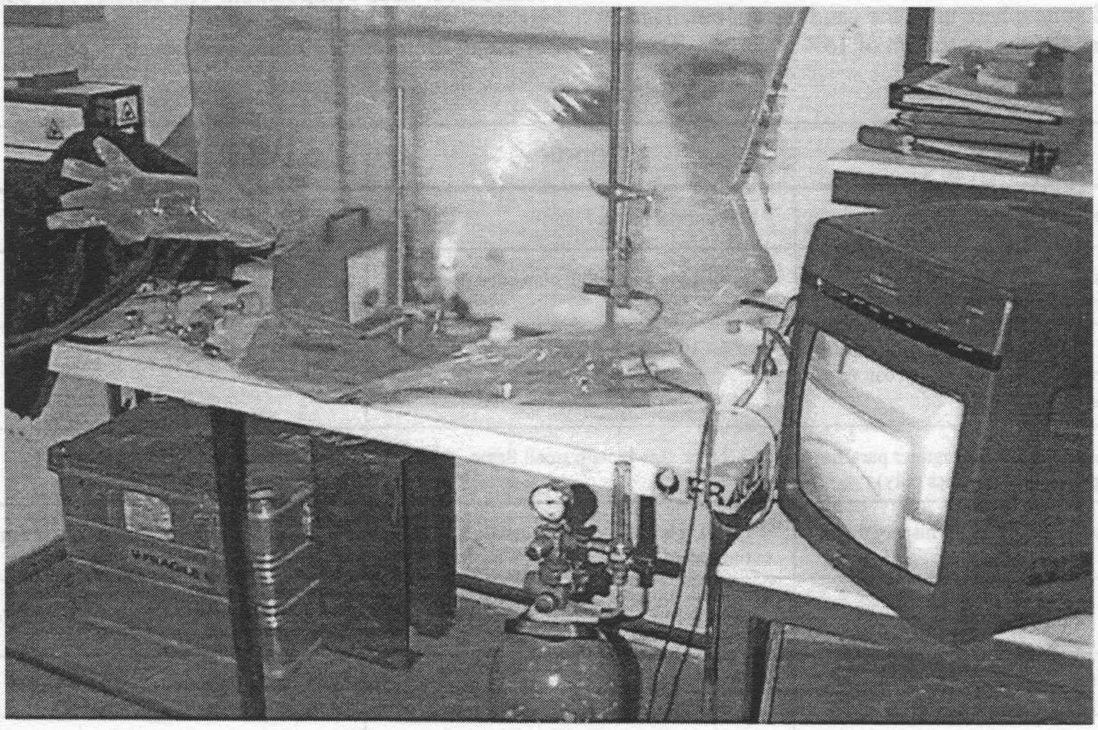

Plate 1. Testing setup using a Teledyne Portable Oxygen Analyser, and large inflatable glove chamber to measure oxygen concentrations which would extinguish various fuels. i.e. matches, candles and butane cigarette lighter.

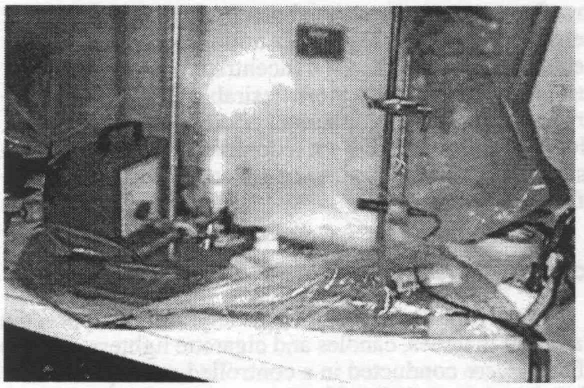

Plate 2. Close-up of experiment. Note mini video camera centre right.

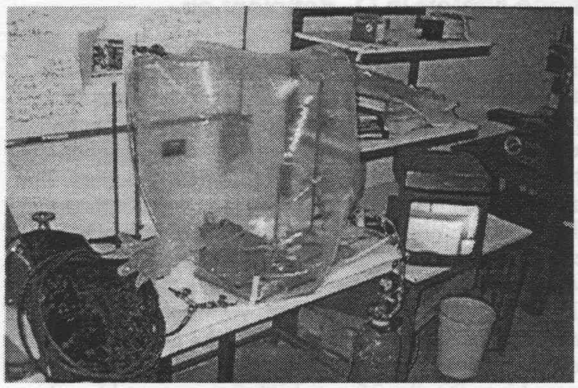

Plate 3. Overall view of experimental setup. Video recorder and argon gas bottle.

When the match tests were complete, the chamber was slowly re-filled with fresh air and a butane cigarette lighter was struck at each 0.5% rise in oxygen concentration. The level at which the butane would remain alight was noted. Then the O_2 concentration was reduced to verify the exact percentage which would extinguish the flame. Both ignition and extinguishing of the flame occurred between 14.25% and 14.5% O_2.

The atmosphere in the chamber was then returned to normal air and a candle lit. Argon was slowly purged into the enclosed atmosphere until the candle went out. This occurred at an O_2 concentration of 15%.

Results

The results of the tests are summarised in Table 7. On the whole the match tests were consistent, with about half a percent variation in the O_2 concentration required for the ignition of paraffin on different matches from the same box observed. The test with "Kangaroo" brand matches (made in Sweden) did not show any sign of fizzing slowly like a sparkler as has been observed in caves It is assumed that the matches used in a cave on those occasions had absorbed some moisture which retarded combustion of the match head or that different brands behave differently because of variations in retardant or head composition. The candles and butane lighters were extremely sensitive to changes in O_2 concentrations at their critical combustion points.

Match	Candle	Butane lighter
21% - 18% easily burns all of match.	>19% normal flame.	
17.5% burns head and flame transfers down paraffin to wooden splint on most occasions	17% - 16.5% burns with elongated flame.	
17% - 16.5% ignited head and on nearly every occasion, burns down onto paraffin coating then extinguishes.	16.5% - 16% flame begins to shrink, but candle remains alight.	
16% - 15.5% ignited head just ignites paraffin coating on splint (some matches only)	16% burns slowly with small flame	
15% - head burns briefly with whispery flame & goes out.	< 15.0%, a burning paraffin candle is extinguished.	> 15% O_2, a butane cigarette lighter can easily be lit and will stay alight.
		14.5% - weak blue flame with orange top, just stays alight
		<14.25% - flame will extinguish
14% match head burns very briefly & goes out.		14% - 13% large flashes of flame but will not stay alight.
<13% head flares & extinguishes immediately (less than 0.5 seconds)		12.5% sparks with partial ignition, small fireballs
		<10% - no ignition, only hot sparks from flint.

Table 7. Gives conditions of flame in relation to O_2 % in the controlled atmosphere

Physiological effects of reduced O_2

In atmospheres consisting of just N_2 and O_2, and where O_2 is at a lower concentration than the normal atmosphere, the human body would be affected in the following manner (Laboratory Safety Manual 1992).

- **O_2 reduced from 21 to 14% by volume**. First perceptible signs with increased rate and volume of breathing, accelerated pulse rate and diminished ability to maintain attention.
- **O_2 concentration between 14 to 10% by volume.** Consciousness continues, but judgment becomes faulty. Rapid fatigue following exertion. Emotions effected, in particularly ill temper is easily aroused.
- **O_2 reduced from 10 to 6% by volume**. Can cause nausea and vomiting. Loss of ability to perform any vigorous movement or even move at all. Often the victim may not be aware that anything is wrong until collapsing and being unable to walk or crawl. Even if resuscitation is possible, there may be permanent brain damage.
- **O_2 reduced below 6% by volume**. Gasping breath. Convulsive movements may occur. Breathing stops, but heart may continue beating for a few minutes ultimately death.

These points indicate that there is very little difficulty is caused by short-term exposure to O_2 / N_2 mixtures down to about 10% O_2. From Tables 3 and 7 it can be seen that the percentage of O_2 which will just not support combustion is approximately 15%. This is well above the concentration which will not support human life. In Tables 3 & 4, the theoretical cave atmospheres contain sufficient O_2 concentration to support life, however the CO_2 concentrations is sufficiently high to be dangerous to cavers.

Physiological effects of increased CO_2

Table 8 summarises the way in which the human body responds to elevated CO_2 in an atmosphere. Gases which create a hazard simply by displacing oxygen are called simple asphyxiants. However it is not the lack of oxygen in a cave which causes the physical symptoms or in extreme cases death, rather it is the increased concentration of CO_2. For example a person can survive several hours in an atmosphere with 3% CO_2 and 12% O_2. On the other hand an atmosphere of 8% CO_2 and 18% O_2 could result in suffocation and death within a few minutes.

The exact percentage and timing will depend on the individuals physiological make-up and tolerance. However, several minutes exposure to a concentration of >10% CO_2 will certainly result in death. For instance exposure to 25% CO_2 or greater, will result in death within one minute, even if there is 20% O_2 in the atmosphere.The "Laboratory Safety Manual (1992)", quotes 0.5% CO_2 as the `Threshold Limit Value Time Waited Average' (TLVTWA). This is the concentration to which a person may be exposed, 8 hours a day, 5 days a week, without harm. The manual also quotes 5% $CO_2$ and above as being `Immediately Dangerous To Life and Health' (IDLH). This is the concentration that will cause irreversible physiological effects after 30 minutes exposure.

Exposure to just 1 to 2% CO_2, for some hours will result in acidosis, even if there is no lack of oxygen. This acid-based disturbance will occur in the human body when the increase in partial pressure of CO_2 is greater than 44 mm Hg. Acidemia will result and secondary mechanisms are initiated by the body that attempt to prevent drastic changes in pH and tend to return the pH toward normal. "Intracellular buffering, via red cell haemoglobin, phosphate, and protein, exchange intracellular sodium and potassium for the excess extracellular hydrogen ion. In addition, hypercapnia leads to an increase in renal hydrogen ion secretion and net acid excretion, as well as an increase in bicarbonate reclamation. Although this response begins early, the maximum effect takes several days." (Clinical Management of Poisoning & Drug Overdose, 1996).

Treatment for exposure to CO_2

For persons exposed to high concentrations of CO_2, remove to a well ventilated atmosphere, keep the person warm and avoid exertion. In severe cases administer oxygen if available but be aware that vomiting and nausea often follow. Persons who have been exposed for short periods, generally recover without serious after effects.

Fire fighting research and CO_2

Fields (1992) studied the use of a new fire extinguishing gas mixture, designed to be used in enclosed spaces. While the actual percentages are not given in the paper, the gas called "Inergen" appears to consist chiefly of argon (Ar) with some CO_2 added. The function of the gas mixture is to reduce the ambient oxygen concentration to less than 15%. The study then goes into great detail about the affect on human life when the O_2 concentrations are reduced to between 15.0% and 12.4%, while the CO_2 concentration is increased to between 3.1% and 4.3%. The research found that the

CO_2%	Comments
0.03	Nothing happens as this is the normal concentration of carbon dioxide in air.
0.5	Lung ventilation increases by 5%.
2.0	Lung ventilation increases by 50%, headache after several hours exposure.
3.0	Lung ventilation increases by 100%, panting after exertion, headaches.
5 -10	Violent panting and fatigue to the point of exhaustion and severe headache. Prolonged exposure could result in unconsciousness and death.
10 -15	Intolerable panting, severe headaches and rapid exhaustion. Exposure for a few minutes will result in unconsciousness and suffocation without warning.
25 - 30	Extremely high concentrations will cause coma and convulsions within one minute of exposure.

Table 8. Physiological effects of CO_2 at various concentrations (Strang, 1990)

addition of CO_2 was beneficial as it induced an immediate and sustained stimulus to increase breathing rates of persons caught in areas flooded with this gas mixture. It was the increase in CO_2 and to a much lesser extent the decreased O_2 which stimulated the respiratory response. For fire fighting Inergen, would be injected into an enclosed space at between 0.4 and 0.7 cubic metres for every cubic metre of room volume. At 40% dilution there would be 3.1% CO_2 and 15.0% O_2, while at 70% dilution there would be 4.3% CO_2 and 12.4% O_2. The paper concludes that the elderly or people with heart diseases (eg. coronary artery disease) but not heart failure would be at some risk of clinically significant hypoxia when breathing 70% Inergen mixture at sea level, but not when breathing a 40% mixture. The use of Inergen was considered at altitudes with barometric pressure down to 650 mm Hg, (Sea level atmospheric pressure ≈ 760 mm Hg). There was an overall increase in risk, however not significant enough to warrant a change in the mixture. At sea level an average healthy person would be at low risk of suffering any affects other than reducing their capacity for physical exertion, to less than half the maximum they could normally sustain while breathing fresh air.

An increase in CO_2 would cause increased breathing rates and could impose serious limitations on the degree of physical exertion achievable by a person with lung disease, cardiovascular disease, anaemia or carbon monoxide poisoning.

This paper fails to mention exposure times in relation to effects on humans at various concentrations of CO_2 and O_2 as would be expected after the addition of different Intergen to an enclosed atmosphere.

Inergen in air	N_2%	Ar%	CO_2 %	O_2%	trace gases %
40%	70.0	11.4	3.1	15.0	0.5
70%	66.5	16.4	4.3	12.4	0.4

Table 9. Resulting volume % of gases in an inergen air mixtures which extinguish fire.

Conclusion

The results and discussion in this paper have clearly answered the four questions posed in the introductory paragraph.

- The Naked Flame Test is primarily measuring the low O_2 concentration.
- It is not reliable for measuring CO_2 concentrations. The Naked Flame Test using different fuels can reliably indicate the O_2 concentration in a cave atmosphere.
- Examination of the literature has shown that a high (>6%) CO_2 concentration is the most life threatening situation encountered underground. A life threatening low (<10%) O_2 concentration is rarely encountered in caves.
- Can the butane lighter be added to the following list of CO_2 indicators (Australian Caver 1990)?

  1% CO_2 a lighted match will go out

  4% CO_2 a lighted candle will go out

  6% CO_2 a lighted carbide lamp will go out.

A butane lighter can be added to the list of Naked Flame indicators of foul air, however as already determined by controlled atmosphere experimental work in this paper, all flame tests are measuring the O_2 content of the atmosphere. CO_2 concentrations at the levels which can be encountered in caves, have no real influence on the Naked Flame Test. Therefore extinguishing of a naked flame is indicating a potentially dangerous cave atmosphere, which is low in O_2 and most likely has an elevated concentration of CO_2. The exact CO_2 concentration can not be determined by the flame test as the cave atmosphere may have been influenced by type 1, 2 or 3 Foul Air or a combination of these. It can only be assumed that instrument inaccuracies occurred when the rule of thumb CO_2 test was originally determined during the early 1970's, in mainly type 2 Foul Air at Bungonia Caves, NSW.

It could be concluded that the Naked Flame Test adopted as part of the ASF Cave Safety Guidelines, 27th Jan. 1990 (Australian Caver 1990) is essentially meaningless. Without sophisticated measuring instruments, one can only speculate about the exact concentration of CO_2, so if any one of these flame indicators will not burn, it is time to exit the cave.

Cavers should recognise the fact that exposure to foul air has an effect on a person's ability to function normally. The likelihood of an accident is therefore greatly increased. All care and precautions should be taken.

If sophisticated measuring equipment is not available, the best advice is to carry out a "Naked Flame Test" when you or a member of your group experiences the first signs of laboured breathing, headaches, clumsiness, loss of energy or any of the other signs associated with elevated concentrations of CO_2. Ideally cavers should become aware of the subtle changes to a cigarette lighter flame associated with O_2 concentrations down to 13%. This will reduce the amount of unpleasant fumes emitted from matches burnt by people experimenting in the confines of a cave. The best advice is, "If in doubt, get out", in an orderly manner.

Acknowledgments

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Review

Caves: Processes, Development and Management
David Gillieson,

Publisher: Blackwell, Oxford. 1996
Reviewer: Armstrong Osborne, University of Sydney

In **Caves: Process, Development and Management**, David Gillieson has succeeded in producing a well-written and readable introduction to the science of caves. The structure of the book, which deals with three themes; the physical development and physical characteristics of caves, the ecology of caves and cave management is well thought out. Major chapters are concluded with a small, but illustrative case study.

As with all introductory texts, it is difficult to determine the exact audience for which the book was written. While the text style and layout suggest the book is intended for a wide audience, some of the diagrams, lifted from standard academic texts, and the equations in the hydrology sections will leave many readers bewildered.

The lists of references at the end of each chapter and the glossary at the back of the book are very useful. The photographs, which have been reproduced in a quite dark and gloomy manner, are a real disappointment.

While the book has received a very warm welcome from Australian cave managers and cavers, it seems to have evoked a quite hostile reception from many of David's Australian academic and scientific colleagues. I always expect specialists to squeal about proof-reading errors, misquotes, all the photos (meaning their unacknowledged photo) being upside down, use of the term "formation" for speleothem and emit the other usual gripes that accompany the release of a book with a colour cover by an international publisher by someone other than themselves, but it struck me that, this time, there was some other issue involved, which I could not put my finger on. This was partly why I avoided writing this review for some months.

In his Preface and Acknowledgments, David begins by saying that his book is "an unashamedly antipodean view of the world of caves" and I'm sure that was what he intended to produce. An antipodean view does come across very strongly in his case studies, his ecology chapter and in the strong commitment to cave conservation and management evident in the last two chapters, which are probably the high point of the book.

In a final attempt to write this review I took the book with me on a meeting trip (no caving for us armchair types) to Wellington Caves. It was there that I saw my problem with the book, at Wellington like many (dare I say the majority of) Australian caves, there is no streamsink and no obvious spring or seep. David, as an Australian member of the international geomorphic community begins his book with the White (1984) definition of a cave and continues to present the currently dominant "(meteoric) water in-water out", view of karst. As a result chapters one two and three smell of hot dogs, gnocchi and roast beef, not multicultural lamb! Simple single phase caves in gently dipping limestone feature from page 88 onward in "The Development of Common Caves" not complex multi phase systems like Jenolan, enigmatic "nothephreatic" caves like Wellington, Cliefden, Walli and Moparabah or the syngenetic caves of our aeolian calcarenites.

The cave sediments in chapter five are fluvial, while Wellington, like many inland Australian caves, has no fluvial sediments, but is choked with aeolian silts, filled with turbidites and has an extremely the complex stratigraphy. Aeolian silts, turbidites, stratigraphic problems and even the application facies models to cave sediments receive little or no attention in this chapter. While it is pleasing to see the late Rado Gospodaric quoted, however, the significant contributions of Kukla, Lozek, Brain and Frank are ignored.

Chapter six presents a good explanation of current dating technologies, but I can't help feeling that while David does comment about ancient caves throughout the book, his heart, like chapters five, six and seven, is firmly in the Quaternary. Australian Carboniferous, Permian and Cretaceous caves and English Triassic caves definitely seem to be off the agenda.

David Gillieson's book has already found a receptive market among those who need a mainstream, well-written introduction to the science of caves and as such it is highly recommended.

Fossil bones from Mamo Kananda, Southern Highlands, Papua New Guinea

T. H. Worthy and T. F. Flannery

Abstract

Fossil bones collected from Mamo Kananda cave system in the Southern Highlands of Papua New Guinea during the 'Muller 82' expedition are described. Twenty six taxa of mammals, and a few birds and amphibians are present. Most of the bones were accumulated by the Sooty owl (*Tyto tenebricosa*) enabling an analysis of this birds prey in the Southern Highlands. The faunas are considered to be of Holocene age as all fossil species are extant, and the fossil sites are within their altitudinal range.

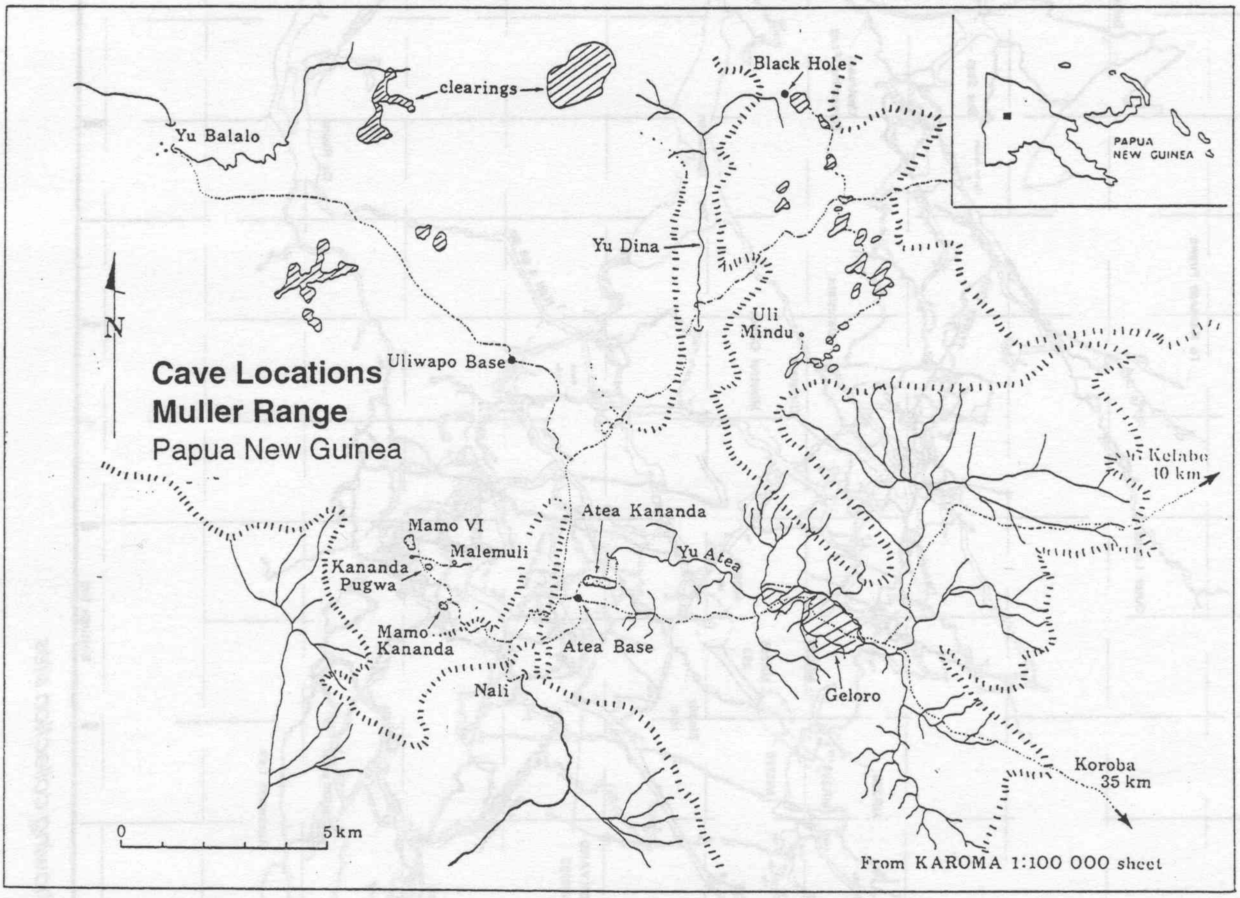

Figure 1. Location map

Introduction

The Muller Range is an extensive limestone plateau in the Southern Highlands where it bounds the Western Province and forms the upper catchment of the Strickland River (Figure 1). One of the Strickland's major tributaries is the Burnett River, which upstream is fed by the Yu Nali. The Yu Nali mainly resurges from a large spring, which drains the Mamo and Geloro areas of the Muller Range. These areas have been the focus of several speleological expeditions (NSRE 1973, Muller 76, Atea 78, Muller 82), which culminated in the mapping of the major caves Atea Kananda (c. 30 km long) and Mamo Kananda (c. 50 km) (James *et al.* 1983). Mamo Kananda was first explored during the Atea 78 expedition from the Mamo IV camp, which was established in Hadia Nduhongairi (MR282). This doline which more or less lies in the centre of the system is at about 2200 m altitude and is located by the grid reference c466796 on the map Sheet 7386 (Ed 1), Series T601. About 300 m to the northwest a stream sinks in a doline called MR299, which is depicted on the topographical map and is shown at c. 5°33'S 142°19'E in James and Dyson, 1980: Figure 11.1. MR282 is a large dry rockshelter, in which a horizontal cave called The Backyard enters. The stream flowing from The Backyard sinks down a narrow slot in the daylight zone of the rockshelter and leads to many kilometres of cave passage. About 140 m northwest of MR282 a second entrance to the system, Hadia Yaneabogairi (MR275), was found. From these entrances about 6 km of passages were explored in 1978. The 1978 expedition also mapped several short horizontal caves linking dolines in the area (James and Dyson, 1980: Map 8.5). One of them, MR286-288 is further described below (Figure 2).

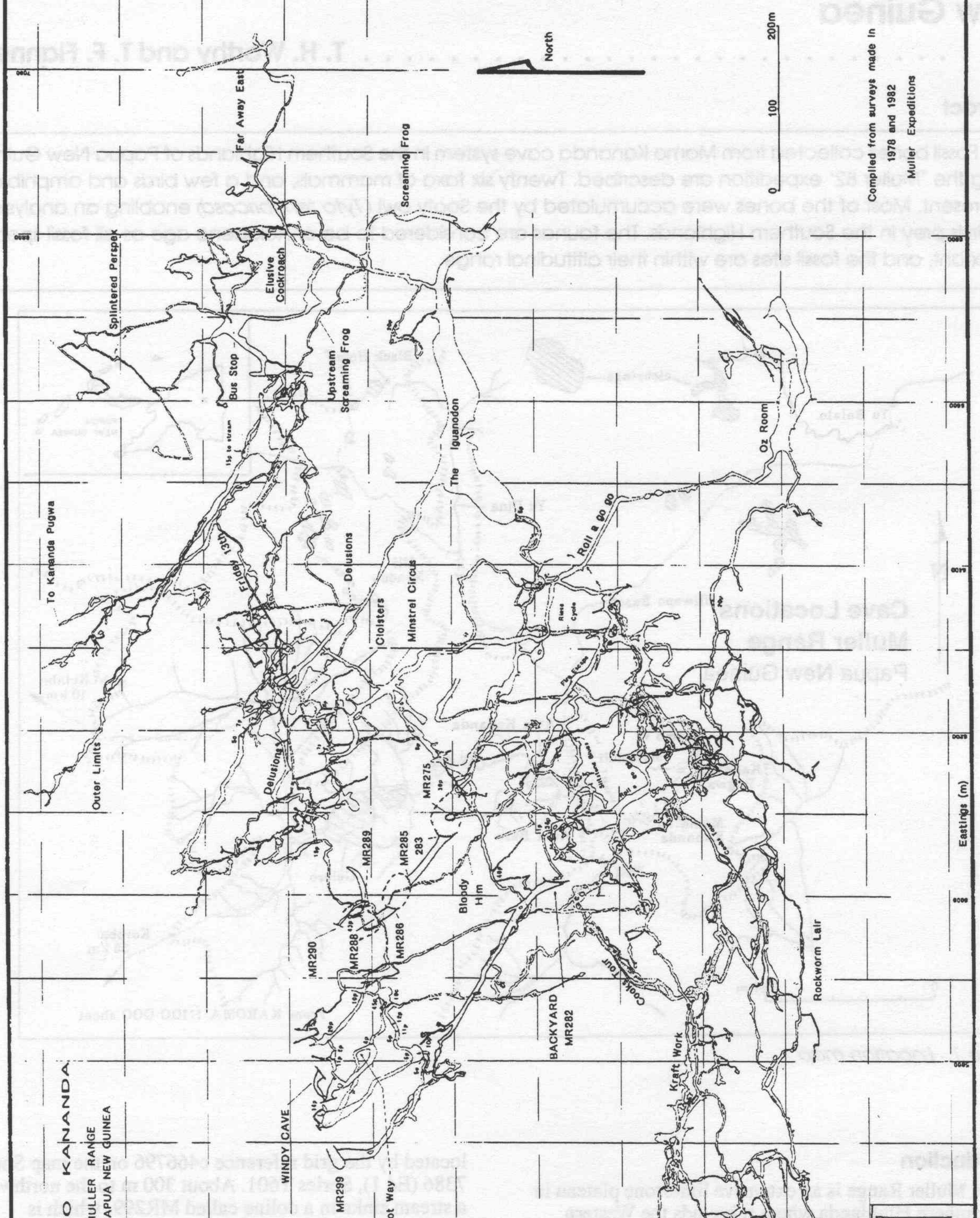

Figure 2 The Southern part of Mamo Kananda showing collection sites

In 1982 the Muller 82 expedition entered the area with one of its main objectives to continue the exploration of the system. Muller 82[1] involved over 50 people and in two months surveyed Mamo Kananda to over 52 km in length (James *et al.* 1983).

Leaptover Entrance is one of the main access points to the system, and just behind the camp fire. In an area of less than 1m^2 hundreds of small mammals bones were found in the talus. Similar deposits of bones were present in other horizontal caves nearby. Other part of the Mamo system also yielded fossil bones.

The fossil bones were taken to New Zealand and catalogued in the Geology Department Museum, Auckland University (AU9479.** to AU9491.**). This paper places this collection on record and makes a preliminary description of the fauna. There are a few bird and amphibian bones in the collection with most being mammals. The species composition of the fauna was assessed from skulls and dentaries, which after initial sorting, were identified by Flannery. The nomenclature used here is that advocated by Flannery (1995).

Mode of deposition of the fossils

The majority of bones were derived from concentrations found on the floor of cave entrances. At MR286 and Windy Cave particularly, hundreds of bones were present. At Windy Cave, which opened into doline MR299, undecomposed pellets and feathers indicated that the bones were derived from owl pellets. While not seen, it seems likely that the owl in question was the Sooty Owl (*Tyto tenebricosa*) which (Majnep and Bulmer, 1977) described as the 'largest of the nocturnal birds and the most ferocious bird of the forest'. They report that it feeds on rats and other small mammals, including the giant rats *Mallomys* sp. (adults of which weigh up to 1.8kg), and especially the ring-tailed possum *Pseudochirulus forbesi*.

Fossils derived from animals that had fallen into the cave down vertical shafts were surprisingly rare, with the most important site being Escargot Way, which is part of MR299. The rarity of fossils in these sites may relate to the fact that most passages in the cave are flushed regularly with large amounts of water due to the high rainfall of the region.

Some bones relate to human activity. James and Dyson (1980) noted that the Bogaye tribesmen had used MR282 for camping, and in the rear of the shelter some bones derived from the animals they consumed were found. In a large dry cave entrance in the valley between the Atea and Mamo camps (c. 490780 on Sheet 7386 (Ed 1), Series T601) bones of the Cassowary (*Casuarius bennetti*) and Pelican (*Pelecanus conspicillatus*) were found. This large, dry cave at about 1940m altitude had no signs of human occupation. The pelican bones were at the rear of the cave and represented two individuals. The senior Duna guide, Kerupa recalled that about 1978 he had shot them and, being an unknown animal to him, he then left their remains in the cave. In 1978, there was an irruption of pelicans out of Australia following severe drought there and birds dispersed as far afield as the Solomon Islands, Fiji, and New Zealand (Marchant and Higgins, 1990).

1. Trevor Worthy was a member of Muller 82 and spent a period of the expedition based at MR282. As a palaeontologist he could not help but notice the bones spilling out of the eroding bank that surrounded the entrance.

Results

The Site descriptions.

The minimum number of individuals represented by cranial elements for each taxon is given for each site in Table 1.

MR286. This is the entrance to a short horizontal cave linking two dolines. Only a few bones of from owl pellets were present and a skeleton of Doria's Tree-kangaroo (*Dendrolagus dorianus*).

Windy Cave. This is a short though cave which leads from the stream-sink doline of MR299 under a narrow ridge to the east. Bones were collected from the surface just inside the eastern entrance and represent a modern prey assemblage of the Sooty owl. A second sample was excavated from within sediment below the surface and so is slightly older.

The Backyard (MR282). Collections from here are of three discrete derivations.

- Human refuse – from the rear of the shelter a few bones of larger mammals were collected which all had greenstick fractures. Such breaks are characteristic of predated bones and as the site was a known camp for people and the species represented are favoured prey of people (echidna and cuscus), it is assumed the bones are the remains of food.
- Owl pellets – in three small areas close to Leaptover Entrance bones were found in the rockfall talus. Specimens from each of three discrete aggregations were kept separate. All of these aggregations were buried between 10-50 cm under talus and so are older than the Windy Cave samples.
- Vagrants – a single skeleton of the Striped Bandicoot *Microperoryctes longicauda* was found in the cave passage where it had died.

Mamo Kananda, discrete sites in the cave. Single bones or part skeletons were found at discrete locations around the cave. Most were swiftlet (*Collocalia hirundinacea*) skeletons, although several skeletons of small bats were also noted. 17 swiftlet skeletons were recorded in the following passages:

- the connection between Kraftwork and Kit Kanyon
- Whirling Person
- Rockworms Lair (3)
- Minstrel Circus
- Escargot Way
- Non-Reflective Surface
- The Cloisters
- Roll-a-go-go (3)
- Sacking of Rome (2)
- Far Away (3).

Swiftlet skeletons were throughout the cave and up to 300 m below the surface and seemingly kilometres from the nearest entrance. However, this is not surprising as these birds were regularly found considerable distances from entrances. Such encounters usually resulted in a frenzied clicking on the part of the bird until it reoriented itself and flew off into the darkness. Skeletons of small bats were rare but one was found in Rockworms Lair and another in Far Away.

Escargot Way, a dry passage leading from MR299, had most remains of 'pitfall-trapped' animals. These included the Coppery Ringtail possum (*Pseudochirops cupreus*), Pigmy Ringtail (*Pseudochirulus mayeri*) and Silky Cuscus (*Phalanger sericeus*). Apart from these, isolated finds were made at Uli Kendi (*Pseudochirops cupreus*), The Cloisters and Outer Limits (*Dasyurus albopunctatus*), Delusions of Grandeur and Whirling Person (unidentified).

Species	Windy Cave		Backyard				MR286	Vagrants	Weight	Altitude
	surface	Lower layer	A	B	C	Human			M-F	m
Tachglossidae										
Tachyglossus aculeatus	0	0	0	0	0	1	0	0	1400-1700	0-1675
Dasyuridae										
Antechinus sp.	6	1	3	1	2	0	0	0	(40-70)	
Dasyurus albopunctatus	0	0	0	0	0	0	0	1 - Outer Limits; 1 - Delusion of Grandeur; 1 – Cloisters	627-	0-3500
Neophascogale lorentzii	0	1	0	0	1	0	0	0	212-	1500-3300
Peroryctidae										
Microperoryctes longicauda	6	3	5	3	2	0	1	1 – Backyard	478-598	1000-3950
Peroryctes raffrayana	0	?1	0	0	0	0	0		865-812	60-3900
Macropodidae										
Dendrolagus dorianus	0	0	0	0	0	0	1	0	10366-8796	600-3300
Phalangeridae										
Phalanger gymnotis	0	0	0	0	0	1	0	0	3000-2410	0-2700
Phalanger sericeus	0	0	0	0	0	1	0	2 - Escargot Way	2039-1967	1500-3900
Burramyidae										
Cercartetus caudatus	13	9	15	0	23	0	0	0	19.8-20.2	1500-3450
Petauridae										
Petaurus breviceps	0	3	4	0	4	0	1	0	88.5-81.6	0-3000
Pseudocheiridae										
Pseudochirulus mayeri	38	40	83	6	67	3	13	1 - Escargot Way	149-154.5	1500-3600
Pseudochirulus forbesi	1	0	0	0	0	0	0	0	732-566	500-2800
Pseudochirops cupreus	0	0	0	0	0	1	0	1 - Uli Kendi, 1 - Escargot Way	1769-1680	1700-3996
Muridae										
?Stenomys sp.	1	4	0	0	20				(40-100)	
Parahydromys asper	0	0	1	0	1				540-	700-2200
?Melomys sp. 1	11	5	9	3	7				(40-100)	
?Melomys sp. 2	4	0	0	0	0				(40-100)	
?Leptomys sp.	11	4	11	0	5				(40-100)	
Coccymys reummleri	1	4	6	0	12				33.4-26	1900-3600
Coccymys sp.	1	2	5	0	4				(25-40)	
?Pogonomys sylvestris	0	0	1	0	5				46.7-40	1300-2800
Bats										
Syconycteris australis	0	6	3	1	0	0	0	0	17.1-17.6	0-3000
Syconycteris sp.	0	0	0	0	1	0	0	0		
Nyctimene ?cyclotis	0	0	3	0	1	0	0	0	35.3-	0-1500
Dobsonia magna	0	0	0	0	0	0	0	1 - Nali Cave	489-317	0-2000
micro-bats	0	2	2	0	1	0	0	1 - Rockworms Lair	(10-20)	
Total MNI	**93**	**84**	**151**	**14**	**156**					

Table 1. A list of the species of mammal recorded from Mamo Kananda showing minimum numbers of individuals (from cranial elements) represented in each site. The weight range for each species is given for males (M) and females (F) from Flannery (1995). The known altitude range for each species is also given from data by Flannery (1995).

In Nali Cave in Nali Gorge at least 600 m lower than the plateau was a colony of Fruit bats. A skeleton of one of these is identified as the Great Bare-backed Fruit-bat (*Dobsonia magna*).

Discussion

A minimum of 26 taxa of mammals is represented in these faunas from cave deposits in the Mamo area of the Southern Highlands of Papua New Guinea. The list will increase when the small dasyurids presently classed as *Antechinus* sp. and the micro-bats are identified. All species are expected for this area of Papua New Guinea.

The geological age of most of these faunas is not known, but an assessment can be made using the faunal composition. Firstly, the material from the surface of Windy Cave was a modern assemblage still being accumulated at the time of collection. As there is no significant difference in the species composition between this site and those in the Backyard it seems that the faunas the owl was preying on were essentially similar. Secondly, the sites are presently at about 2200 m altitude which is within the known range for all species in the assemblages. Studies of other faunas in the Irian Jaya/ Papua New Guinea region have shown that in the Pleistocene, cooler and drier conditions resulted in lowered vegetation zones so that areas presently in tall montane forest at 2000-3000 m were then in grassland-shrubland habitats similar to those now found above 4000 m (Flannery, 1992; 1997; Hope *et al.* 1993). These Pleistocene faunas usually also contain some extinct taxa. The fossil faunas from Mamo include no species typical of higher altitudes and no extinct taxa. They are thus interpreted as of mid to late Holocene age.

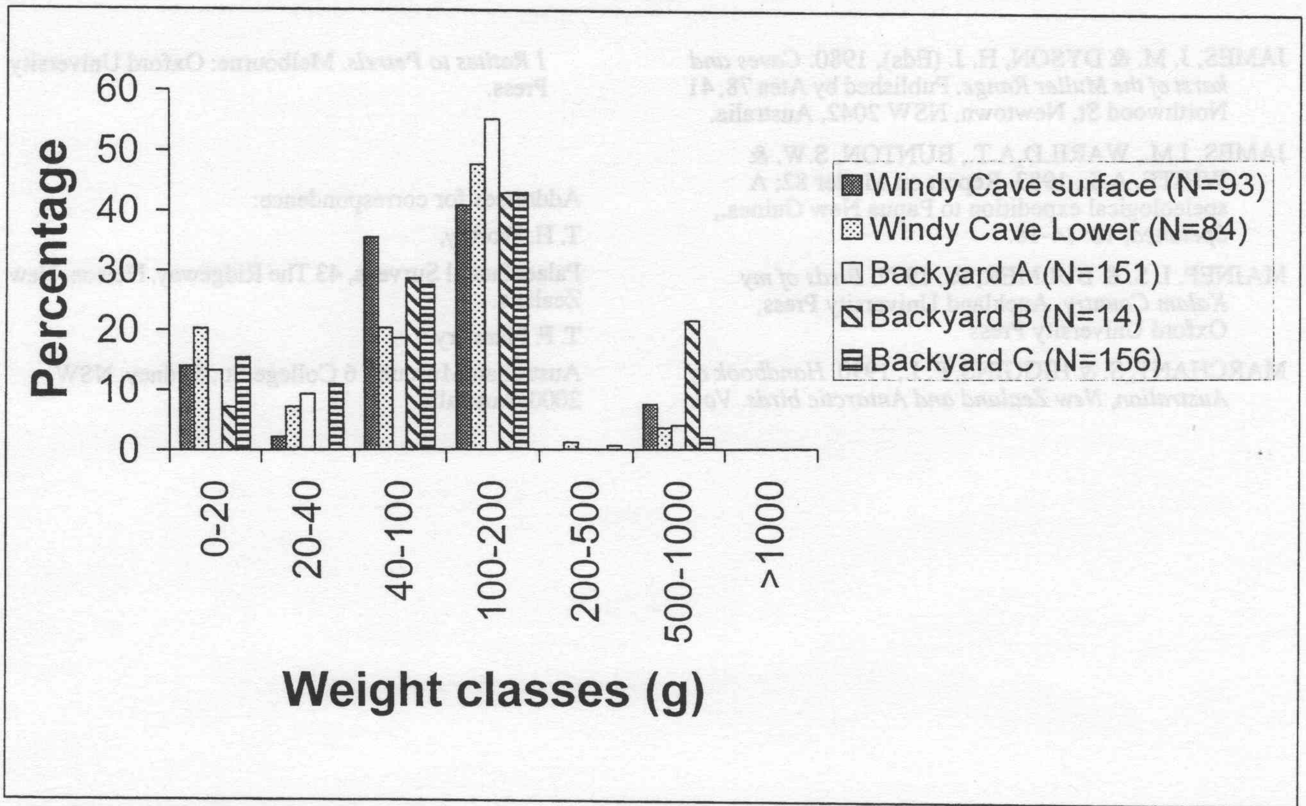

Figure 3 Weight classes of Sooty owl prey

The collections from Windy Cave and the Backyard provide data on the diet of the Sooty Owl in this highland region of Papua New Guinea. These faunas contain 18 mammal taxa, and in each site the species have a similar frequency. In all faunas, the most numerous species is the Pygmy Ringtail Possum (*Pseudochirulus mayeri*), and second most abundant is the Long-tailed Pygmy Possum (*Cercartetus caudatus*). In addition, there were a few small dasyurids (*Antechinus* sp.), Striped Bandicoots (*Microperoryctes longicauda*), Sugar Gliders (*Petaurus breviceps*), up to eight species of rodent, Common Blossom Bats (*Syconycteris australis*), a bat that is probably the Round-eared Tube-nosed Bat (*Nyctimene cyclotis*), and rare micro-bats. There is little comparative data available concerning the diet of Sooty Owls in Papua New Guinea. Flannery (1997) reported on the composition of a fossil fauna in Kelangurr Cave at 2950 m in Irian Jaya and attributed 13 of the 16 mammals to prey of the Sooty Owl, and noted the presence of a few birds.

The prey species in the owl-derived faunas were classed by weight using data given in Table 1 and the results plotted in Figure 3. This clearly shows that the Sooty Owl preferred prey in the size range of 100-200 g but took prey up to a kilogram in weight. In these sites, most of these bigger animals were the Striped Bandicoot, which ranges from approximately 500-600 g. The Sooty Owl thus takes a a wide range of species including amphibians and birds, but concentrates its attention on small mammals less than one kilogram in weight and preferably in the 100-200 g range.

The larger animals were rarely found in deposits in Mamo Kananda. A single Short-beaked Echidna (*Tachyglossus aculeatus*) was represented in the Backyard among bones eaten by people. In 1982, the Duna hunters caught and ate a Long-beaked Echidna (*Zaglossus bruijni*), and James and Dyson (1980) also recorded this species as prey. Both echidna species are therefore present in the area. Bones of only one tree-kangaroo (*Dendrolagus dorianus*) were found. The Duna like to hunt these animals and several were caught during Muller 82. The Ground Cuscus (*Phalanger gymnotis*) and the Silky Cuscus (*P. sericeus*) were the only cuscus represented in the fossil deposits. Both were in the assemblage attributed to human activity. The remaining large animal in the assemblages is the Coppery Ringtail (*Pseudochirops cupreus*) which is the largest ringtail and a favoured game animal. Cassowary bones were not found in Mamo Kananda despite the exploration of numerous vertical shafts entering the cave system. The only bones found were in a dry cave in the valley between the Mamo and Atea plateaus, and were probably left there by hunters.

Acknowledgments

Figure 1 was drawn by Alan Warild and Figure 2 is reproduced from draft copies provided by Mark Laurendet who with Dirk Stoffels is producing a detailed complete version. THW thanks the organisers of Muller 82 for providing the opportunity to go caving in PNG. We thank Professor Jack Grant-Mackie, Auckland University, for the curation of the specimens and facilitating their study.

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Information for Contributors

Scope

Contributors from all fields of study related to speleology will be considered for publication. Suitable field include Earth Sciences, Speleochemistry, Hydrology, Meteorology, Conservation, Biospeleology, History, Major Exploration (Expedition) Reports, Equipment and Techniques, Surveying and Cartography, Photography and Documentation. Comprehensive descriptive accounts of the exploration and morphology of individual caves will be welcomed, but simple trip reports and brief cave descriptions are not adequate. Papers overall should not exceed 20 printed pages in length. Contributors intending to write at greater length or requiring any advice on details of preparation are invited to correspond with the Editors. All manuscripts will be read by referees. Short "Letters to the Editor", expressing a personal view or giving a preliminary report of interesting findings, are welcomed, and will be given preference for speedy publication.

Manuscripts

Submitted manuscripts should be in final form ready for publication. As proofs are not normally sent to authors particular care should be taken to check for typing errors. Manuscripts should be typed, double spaced, on one side of the paper. The title should be upper case bold and the author's names should follow. A brief and explicit summary of the notable aspects of the paper, headed abstract, should precede the main text.

Throughout the main text headings should be in upper case, centred and bold, while subheadings should use lower case bold aligned with the left margin. Acknowledgements should be placed at the end of the text before the references, and the author's addresses for correspondence should follow the references.

Authors are requested to submit a copy of their manuscript on floppy disk as well as hard copy in the first instance. Disks may be 3 1/2" or 5 1/4" in either MSDOS or Macintosh format. If sending text as a word processing document (Microsoft Word etc.), please send a copy as text on the same disk.

References

References should be listed alphabetically at the end of the manuscript and cited in the text by the author's name and the year of publication (e.g. "(Grey, 1988)"). Where there is more than one reference to the same author in one year the letters a, b, c, etc. should be added. If there are more than two authors, they should all be named at the first citation and in the reference list, but the first name followed by *et al.* should be used in subsequent citations. References should be checked particularly carefully for accuracy. Journal titles should be abbreviated following the "World List of Scientific Periodicals", which is available in most large libraries.

The following examples illustrate the style:

GREY, M.R., 1973 Cavernicolous spiders from the Nullarbor Plain and south-west Australia. *J. Aust. ent. Soc.* 12: 207-221.

VANDEL, A., 1965 Biospeleology. *The Biology of the Cavernicolous Animals.* Pergamon, London. Pp. xxiv, 524.

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.

Illustrations

Figures and photographs should not duplicate information in tables or other material. Photographs should be clear black and white prints with sharp focus. The number of pages with photographs will be kept to a minimum. Where several photographs are to form one plate they should be mounted together on white card. Any lettering required on photographs should be applied with "Letraset". Figures should be drawn in Indian ink on white card, heavy paper or tracing material and lettered using stencils or "Letraset" or supplied as Laser prints. Most computer drawn documents can also be handled if they are in Macintosh format. Please avoid using unusual fonts unless they are included with the diagram.

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Contents

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