KEYWORDS: ***Finger lines - Travertine speleothem - Isotopic geochemistry - Dating - Speleoclimate***

The speleothem medium of finger flutings and its isotopic geochemistry

ROBERT G. BEDNARIK

Abstract. The isotopic geochemistry relating to the re-precipitation of calcite in caves containing rock art is considered, in terms of theory, natural manifestations, and relationship with questions of radiometric dating of carbonate speleothems. Specific forms of such deposits are considered, together with the various modification processes to which they are subjected, and the palaeo-environmental significance of both speleothems and their modifications. More specifically, particular forms of rock art found within, as well as on or under, such deposits are examined, such as finger flutings commonly found in caves of southern Australia. Some of the variables relating to their occurrence are elucidated, their preservation and possible dating is reviewed in the light of these factors, and new radiometric data from South Australian caves are introduced and discussed. The paper indicates the severe limitations likely to apply to radiocarbon dating results from carbonate speleothems, and in relating them to the archaeological features that are often physically associated with them. Caution is advocated in the interpretation of empirical data derived from such deposits, and possible future research goals are identified.

FINGER flutings (*sillons digitales*) are a specific type of rock art occurring only in caves, and found so far in two regions in the world. One is southern France and northern Spain, the other Australia and Papua New Guinea (Bednarik 1984, 1985, 1986a, 1990a; Ballard 1993). At most of these sites, the *mont-milch* bearing finger flutings is of the speleothem type, but states of preservation differ profoundly between different sites, and often even within an individual cave (Figure 1). In most cases the original deposit is sufficiently well preserved to be still recognisable; in many it has been modified by natural processes, but even then the medium appears to have been soft and pliable at the time the finger flutings were produced. I intend in this paper to examine the nature of this medium, and to determine whether any archaeologically or speleologically significant deductions can be made from it.

If we wish to determine the merits of a geomorphological and geochemical examination of the medium of ancient finger markings, of dating clues derived from it, and of correlating these data with other information, we need to acquaint ourselves with the nature of speleothems (Moore 1952), with the effects of modification processes on them, and with the significance of different states of preservation. In addition, we should consider how cave contents may act as palaeoclimatic indices.

Carbonate speleothems

One of the most obvious characteristics of the vast majority of caves is that they are a phenomenon typically found in limestone. This sedimentary rock of a largely organic origin is readily soluble in aqueous carbon dioxide, and, owing to the bedding and joints it commonly forms, is also susceptible to tectonic adjustments. Broadly speaking, these are the two main reasons for the formation of limestone caves, although other factors may contribute as well.

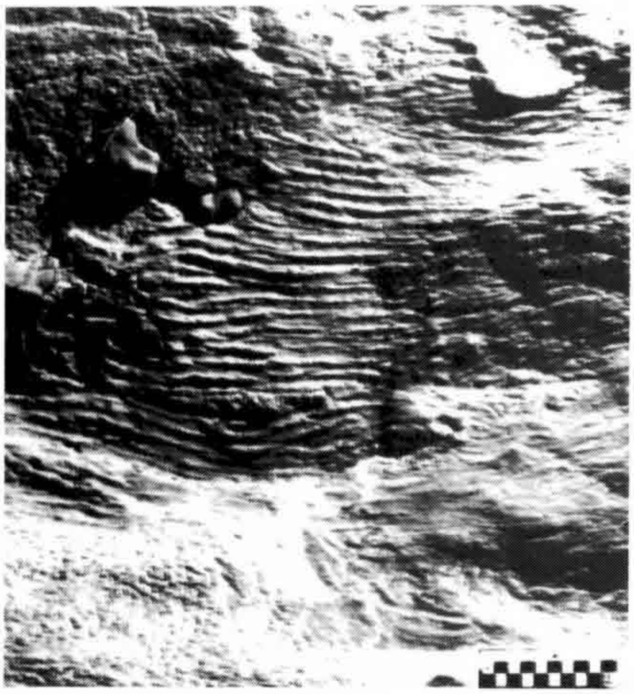

Figure 1. *Desiccated finger flutings on vertical wall, with subsequent slight cover of speleothem, but otherwise well preserved. Karlie-ngoinpool Cave, South Australia.*

Speleothems result from the responses of particular rock constituents to atmospheric/hydrospheric conditions in a cave space. They are formations of precipitated compounds such as chlorides, nitrates, sulphates and — most importantly — carbonates. Calcite, dolomite and aragonite generally form carbonate speleothems or travertine. They occur in a number of modes, for example as the familiar stalactitic growths, as dripstone curtains, helictites, straws, cauliflower formations, and as cutaneous flowstone formations of various forms. Consisting usually of comparatively pure calcite deposited in crystal form, the size of these crystals and their mode of arrangement and spacing may differ substantially. They may be massive and densely packed, or they may be very small and widely spaced, rather like the minute water crystals of snow flakes. Travertines are generally precipitated from calcium bicarbonate solution, which in the case of speleothem carbonates forms as carbon dioxide-enriched water percolates through limestone beds and chemical equilibrium is established:

$$xCaCO_3 + H_2O + (x + y)CO_2 \rightleftharpoons xCa(HCO_3)_2 + yCO_2, \qquad (1)$$

where x and y are the molecular concentrations respectively of free and locked carbonic acid, and are subject to the correlation $y = K(T)x^3$, K(T) being a temperature-related constant (Wendt et al. 1967). Actually, the relationship is significantly more complex than is suggested by this reaction, but it will suffice in the present context. The condition of electroneutrality pertaining to it can be summarised as:

$$C_{H^+} + 2C_{Ca^{2+}} - C_{OH^-} - C_{HCO_3^-} - 2C_{CO_3^{2-}} = 0, \qquad (2)$$

where C_{H^+} is the concentration of hydrogen ions (moles/litre).

Limestone is dissolved by a combination of two processes which relate to the isotopic composition of the calcite precipitated in carbonate speleothems: the open and the closed systems. The carbon dioxide is usually derived from vegetation above the cave, which has either obtained it via photosynthesis and then released it after oxidation of dead plant matter, or has given rise to a community of mycorrhizal soil micro-organisms which then respire the gas. The concentration of species in an aqueous solution of carbon dioxide are given by:

$$C_{CO_{2(aq)}} = \frac{C_{H^+}\left((C_{H^+})^2 - \frac{K_W}{\gamma_{H^+} \cdot \gamma_{OH^-}}\right)}{\frac{K_1\,\gamma_{CO_2\,(aq)}}{\gamma_{H^+}}\left(\frac{C_{H^+}}{\gamma_{HCO_3^-}} + \frac{2K_2}{\gamma_{H^+} \cdot \gamma_{CO_3^{2-}}}\right)}, \qquad (3)$$

where γ_{H^+} is the activity coefficient of hydrogen ions.

Calcite is thus dissolved and mobilised up to equilibrium concentration. If one of the factors determining the value of equilibrium concentration is altered, establishing conditions for a new equilibrium may demand the precipitation of the surplus solute, leading to travertine formation. Evaporation of water, to which the formation of stalactitic growth is sometimes attributed, is therefore not important in the formation of travertine. Evaporation is, in fact, nearly impossible in those caves that boast the most abundant travertine deposits, because their air humidity usually exceeds ninety-six per cent. On the other hand, caves with a low humidity (small or shallow caves) normally have only limited speleothem growth.

The ability of water to hold carbon dioxide in solution is related to factors such as temperature, turbulence and pressure. Pressure changes dramatically in the bicarbonate solution when it reaches the ceiling of a cavity. While travelling within the rock's interstitial spaces, the solution is subjected to the quite considerable pressure of the closed system. The parietal space, however, experiences atmospheric pressure and this causes the release of surplus calcite as the solution emerges in the cave. It will be in oxygenous isotopic equilibrium with the water if the rate of loss of carbon dioxide is sufficiently slow to maintain the equilibrium between the bicarbonate ions and the aqueous carbon dioxide. If, however, the rate of loss of carbon dioxide from the solution is so rapid that isotopic equilibrium cannot persist between the bicarbonate ions, the aqueous carbon dioxide and the water, a kinetic isotopic fractionation will occur between them and will be reflected as a simultaneous enrichment of ^{13}C and ^{18}O in the calcite precipitated (Mills and Urey 1940; Craig 1953; Franke and Geyh 1970; Hendy 1971; Milliman 1974: 7-12).

Montmilch occurs in at least two generically discrete forms. I use the name for this phenomenon that has in my view precedence, being derived from the Swiss *Monmilch*, first attested in scientific literature in 1555, and used by Swiss sedimentologist Schmid (e.g. 1958, 1963), based on her teacher Lais (1940) and other authorities. The English word *moonmilk* is a translation of the German *Mondmilch*, itself probably a corruption of *Monmilch* (apparently referring to mining gnomes rather than the moon), although the etymological origins of that term are uncertain. There is a second explanation, linking the original name to the Latin *lac lunae*, and a third, linking it to *Mont*, in the sense of *mountain*, *montane* etc. The substance was mined in Europe in the Middle Ages and used by rural communities as an ophthalmic analgesic (Bednarik 1986a), as a substitute for zinc oxide. One of its colloquial names is *Nix* (in Lower Austria), which is a corruption of the Latin *nihilum album* ('white nothing'). In Styria, the local name was *Galmei* or *Galmey*, and the modern name in Austria, attested for some centuries, is *Bergmilch* ('mountain milk').

One of the genetically discrete forms of *montmilch* (henceforth with lower case initial, to show that it is being used as an etymologically adopted foreign term) is a precipitate of an initially pure-white deposit of calcium carbonate whose consistency ranges from downy soft —

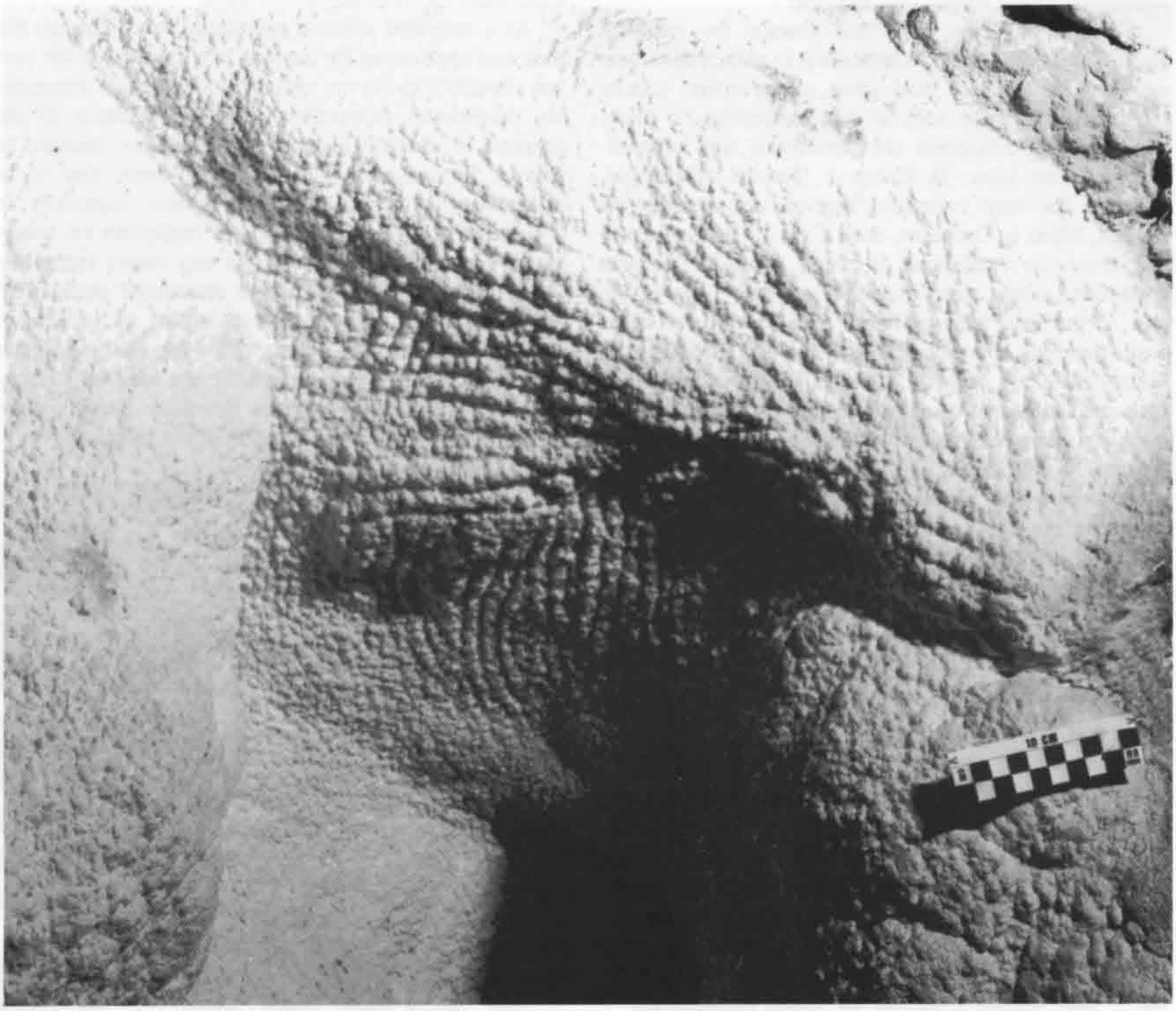

Figure 2. *Finger-marked ceiling of narrow passage, on luxuriant travertine, with extensive subsequent speleothem growth. Karake Cave, South Australia.*

offering no more physical resistance than freshly fallen snow — to being pasty or clayey. The very substantial pores formed by its lattice of minute calcite crystals usually contain much water, often over fifty per cent of the total mass (this represents almost seventy-five per cent of volume). The huge deposits of this substance found in the caves of the European Alps may be over a metre thick, and may form stalactites but no stalagmites (for instance in the Goldgrube, Galmeiloch, Nixlucke, all in Austria), a phenomenon I have seen in only one Australian cave, Karake Cave (South Australia) (Figure 2). The efflorescent, thin and comparatively dry deposits usually found in drier regions, such as Mediterranean Europe and Australia, probably require little solvent activity for their growth.

A second type of *montmilch* is not a speleothem (i.e. it is not re-precipitated), but consists of a highly porous 'skeleton' of formerly dense rock, apparently the result of some process of decay which remains as yet unexplained. The classical Australian occurrence of this form of *montmilch* is that of Koonalda Cave, South Australia. The influence of micro-organisms has been proposed in connection with this phenomenon, but it has not been demonstrated satisfactorily. Irrespective of the different processes that may contribute to the formation of *montmilch*, their products are sufficiently similar to have been combined in this single category. *Montmilch* has often been described as clay, especially in French, British and Australian literature, but it differs significantly even from *argile blanche* (Schmid 1958: 20), or *Tonsinter*, a clay with a high carbonate content consisting of grains transported by moisture. Although quite abundant in a few regions, *montmilch* is not common in most of western Europe or in Australia. The usually drier, more friable character of the comparatively rare Australian deposits is a result of climatic factors, the sparseness of vegetation, the low relief of limestone formations, and the consequent shallowness of caves (although this certainly does not itself inhibit *montmilch* formation; see Bednarik 1965).

Alteration of the finger line medium

Perhaps the most profound change the humanly marked deposits have experienced is desiccation and superimposition of a hard crust of travertine (calcite speleothem) of up to forty or fifty millimetres in thickness. Such modifications are particularly well exemplified at three sites. In Croze à Gontran (Dordogne, France), the hard cutaneous deposit is comparatively smooth, while in Orchestra Shell Cave (Western Australia), travertine exudations of pearly to cauliflower-like speleothem cover many discernible finger lines of the part of the cave known before I discovered its dense south-western concentration (Bednarik 1987-88). In Malangine Cave (South Australia), various stages of such concealment can be observed. In extreme cases, the markings have been exceptionally well preserved due to subsequent desiccation (Figure 3), while at the other end of the spectrum, abundant decorations of cauliflower travertine are still underlain by a subcutaneous zone of soft, and slightly moist, white calcite. The travertine may reach a thickness of some centimetres and all but obscure the finger fluting. Many of the lines are only represented by a thin cleft in the exuded travertine's surface, accurately tracing the course of the digital line beneath it (Figure 4; see also Figure 14). This brings to mind Breuil's (1952: 194) report of a phenomenon where secondary calcite migration is impeded by the moisture-repellent nature of the painted lines of cave paintings.

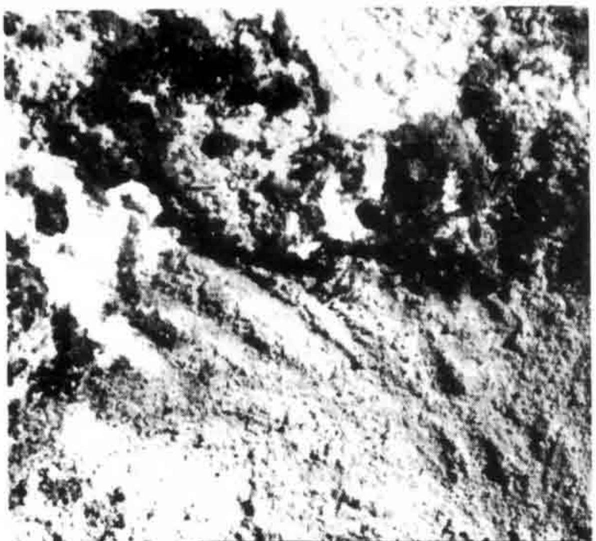

Figure 3. *Well-preserved finger flutings on fossil* montmilch, *disappearing under very heavy subsequent growth of pearly travertine. Ceiling of Malangine Cave, South Australia.*

Both human and other animal markings on cave walls or ceilings can be significantly modified by later deposition of speleothems. Since these modifications promote misinterpretation of the animal markings by archaeologists (Bednarik 1991a, 1994a, 1998a) it is important to consider the modification processes in detail and to try to understand the mechanisms involved.

As a saturated solution percolates down through the rock and approaches the surface of a cave roof, the carbon dioxide's ability to retain the bicarbonate presumably deteriorates proportionally to the decrease of the pressure to which it is subjected. However, because of gravity, precipitation is favoured at lower, that is, at protruding features of the roof surface, especially in conditions of high humidity, or of negligible air movement. Initially the salience of the tiny ridges separating the finger lines is sufficient to encourage preferential deposition. Eventually the development of substantial calcitic exudations is favoured by the limiting factor apparently imposed by the distance the solution is capable of travelling through the deposit's lattice before equilibrium demands precipitation of the solute.

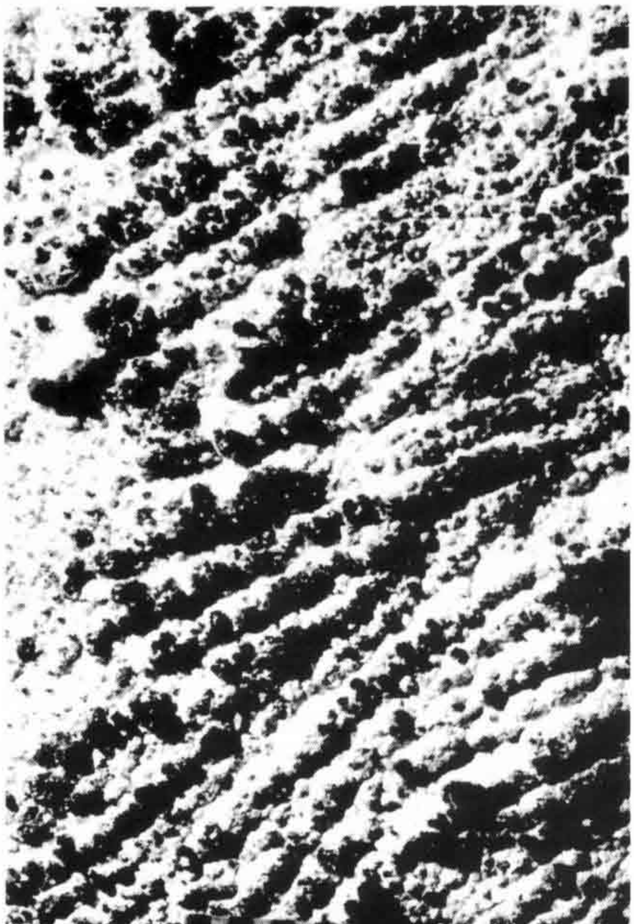

Figure 4. *Heavy speleothem growth covering finger flutings on the ceiling of Malangine Cave, South Australia. For section, see Figure 14.*

A second mechanism may also contribute to retard speleothem growth in the grooves. *Montmilch* consists of an extremely delicate arrangement of calcite crystals which is demolished when the deposit is marked. The destruction of the lattice is most severe in the grooves, and appears to result in the retardation there of subsequent carbonate migration. The visual end-effect of the excrescences may be likened to that of the old and overgrown scars often seen on the bark of trees.

The result of such a process — whatever its precise mechanisms may be — can render former finger lines difficult to recognise; its influence is demonstrated by Hallam's (1971) pronouncement that the rock art in Orchestra Shell Cave was almost certainly not done with fingers. Much of the finger line decoration in Malangine Cave and in many other sites is concealed beneath an even more dense travertine growth than that occurring in the pre-1984 part of Orchestra Shell Cave. The dense finger flutings in the 'new' part of that cave (Bednarik 1987-88) are almost free of speleothem cover.

Subsequent speleothem development over finger lines is, however, not the only modification they experienced. None of the ancient markings have survived without any form of alteration, and with the exception of the few instances (less than ten known in the world) where dried out finger flutings remained practically unworn, all others have been modified by either reductive or additive processes. My attempt to categorise these has resulted in the formulation of five typical classes, illustrated in Figure 5 and described below. It must be emphasised that intermediate and composite forms of alteration abound, and that my types are idealised concepts rather than descriptions of the full spectra of such phenomena one observes in the field. At most sites, more than one of these altered forms occurs; nevertheless, the sites I nominate to characterise the respective types are those that seem to typify these classes most readily.

Figure 5. *The typical classes of modifications of finger flutings, depicted schematically: from the top, each section shows the primary rock of the cave roof, on which the* montmilch *formed and was marked by fingers.*

0 - Fresh (and recent) finger flutings seen in section: examples occur in Rouffignac, Koonalda and Mandurah Caves.

1 - Corrosion has removed some of the surface, resulting in coarsening: Rouffignac, Baume Latrone, Cosquer, Koonalda and New Guinea 2 Caves.

2 - Cutaneous travertine has covered the flutings, but preserved their outline well: Plafond des 'Hiéroglyphes' in Pech Merle, Mooraa, Drop Drop and Nung-kol Caves.

3 - Dense travertine skin has concealed finger flutings and distorted them to appear as narrow grooves: Croze à Gontran, Kriton, Prung-kart and Orchestra Shell Caves.

4 - The montmilch *medium has been gradually dissolved, which exposed the primary rock: Ossuaire in Pech Merle, Yaranda, Gran Gran and Koongine Caves.*

5 - Pearly travertine exudations have formed selectively, avoiding the grooves and accentuating the ridges between them: Malangine, Karake, Snake Hill and Orchestra Shell Caves.

(1) The unmodified finger grooves on a *montmilch*-covered cave ceiling or wall are smooth, and separated in section by acute, pronounced ridges in the direction in which the strokes were executed (Figure 5-0). Very fine striations can sometimes be discerned within grooves, or transverse 'tear marks' which indicate the direction in which the fingers moved (Bednarik 1986a, 1991b). Even if the equilibrium between the factors determining the state of the *montmilch* remains fairly stable throughout

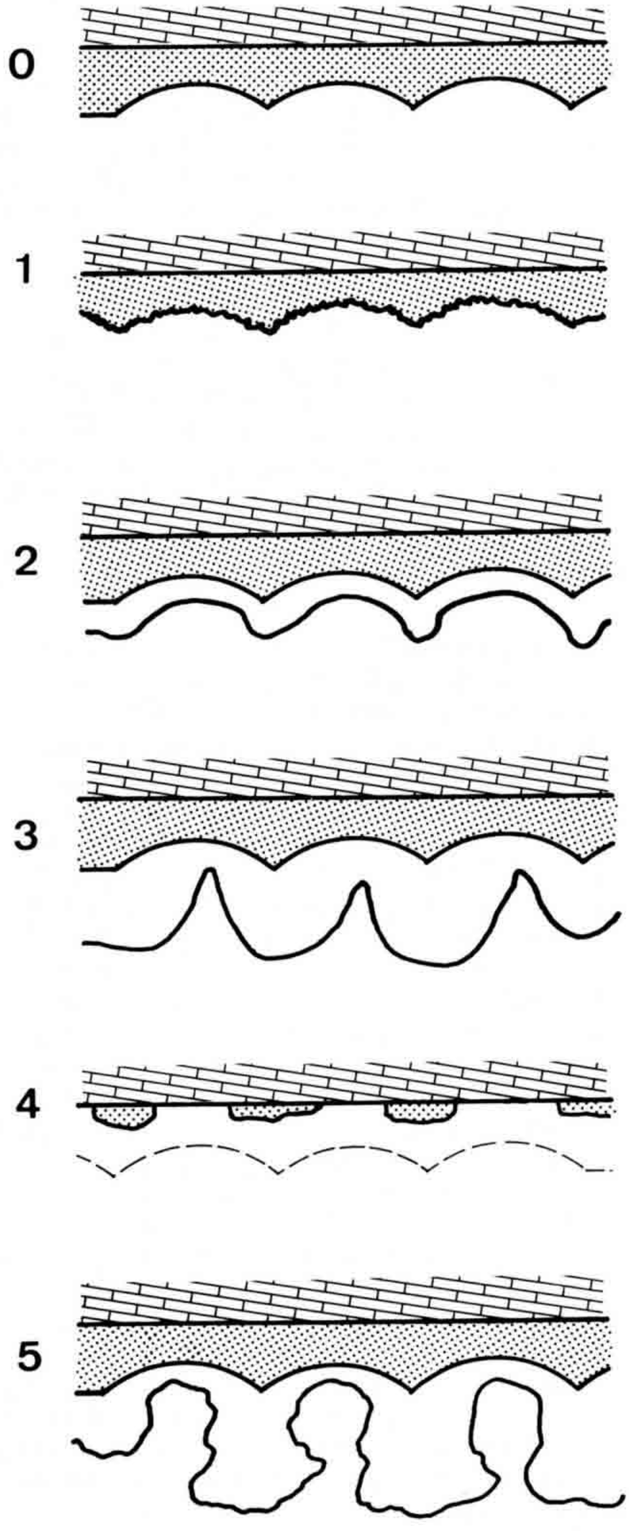

Figure 6. *Extensive ceiling arrangement of finger flutings, the* montmilch *medium of which is largely dissolved. Yaranda Cave, Victoria.*

its history, permitting the deposit to stay soft and somewhat moist, the delicate surface of the precipitate cannot remain totally unchanged over periods of many millennia. Once precipitation has ceased, **surface corrosion** (probably by the moisture held in the crystal lattice and made aggressive by atmospheric carbon dioxide) will set in and coarsen the texture (Figure 5-1; see also Figures 1, 7). Also, owing to the persisting softness of the argillaceous deposit, it is susceptible to damage by biological agencies, most notably the abrasive action of bat wings. *Montmilch* has survived in this mode since the time the lines were made only in deep cave systems, where the speleoclimate was well isolated from external conditions and air residency rates were very high.

(2) An uncommon occurrence is the fairly even **covering** of the finger grooves by a sheet of travertine deposit, with some thickening at the ridges (Figure 5-2).

(3) A comparatively **dense travertine skin** may conceal all surfaces, but instead of filling in finger lines, sometimes the deposition within the depressions has been inhibited, resulting in narrow grooves of pointed section which may resemble incised cuts (Figure 5-3; see also Figures 11, 12, 15). At Croze à Gontran, these occur on both walls and ceilings, which suggests that the deposition process is not influenced by gravity but is perhaps more closely related to the inability of the disturbed *montmilch* lattice to convey further migratory carbonates where it is marked.

(4) In contrast to most other types of alteration, the process can be of a deductive kind. The clearest and perhaps most instructive examples of this are found in the Victorian site Yaranda Cave and in the easternmost part of the Ossuaire, a section of Pech Merle (Lot, France), where all stages of the process are present: the initial speleothem, resembling the above Type 1, is **dissolved slowly** (Figure 5-4; see also Figures 6, 9). The disintegration affects the actual finger lines at a much greater rate, apparently because the compressed *montmilch* lattice is more susceptible to the dissolving process. The effect resembles the thawing of snow on a road: it melts first in the vehicular tracks where the snow (i.e. its crystal structure) has been compressed. The white *montmilch* is first dissolved in the finger grooves, their course being then indicated by stripes of reappearing primary rock. As the precipitate decays further, its residual arrangements also wane until they completely disappear. Yet they are still perceptible even after the *montmilch* is dissolved completely, because a dark film then remains behind — rather like the dark residue one may detect after the spring thaw on the ground (Figure 6). On snow, this residue may consist of dust and other airborne matter formerly dispersed in the snow matrix; in the case of the *montmilch* it is of non-carbonate matter, possibly of colloids, small particles and organic matter that had been deposited in the lattice.

(5) A more extreme form of the selective deposition described above is mostly restricted to ceilings. Distortion ('sagging') evident on similar deposits on sloping

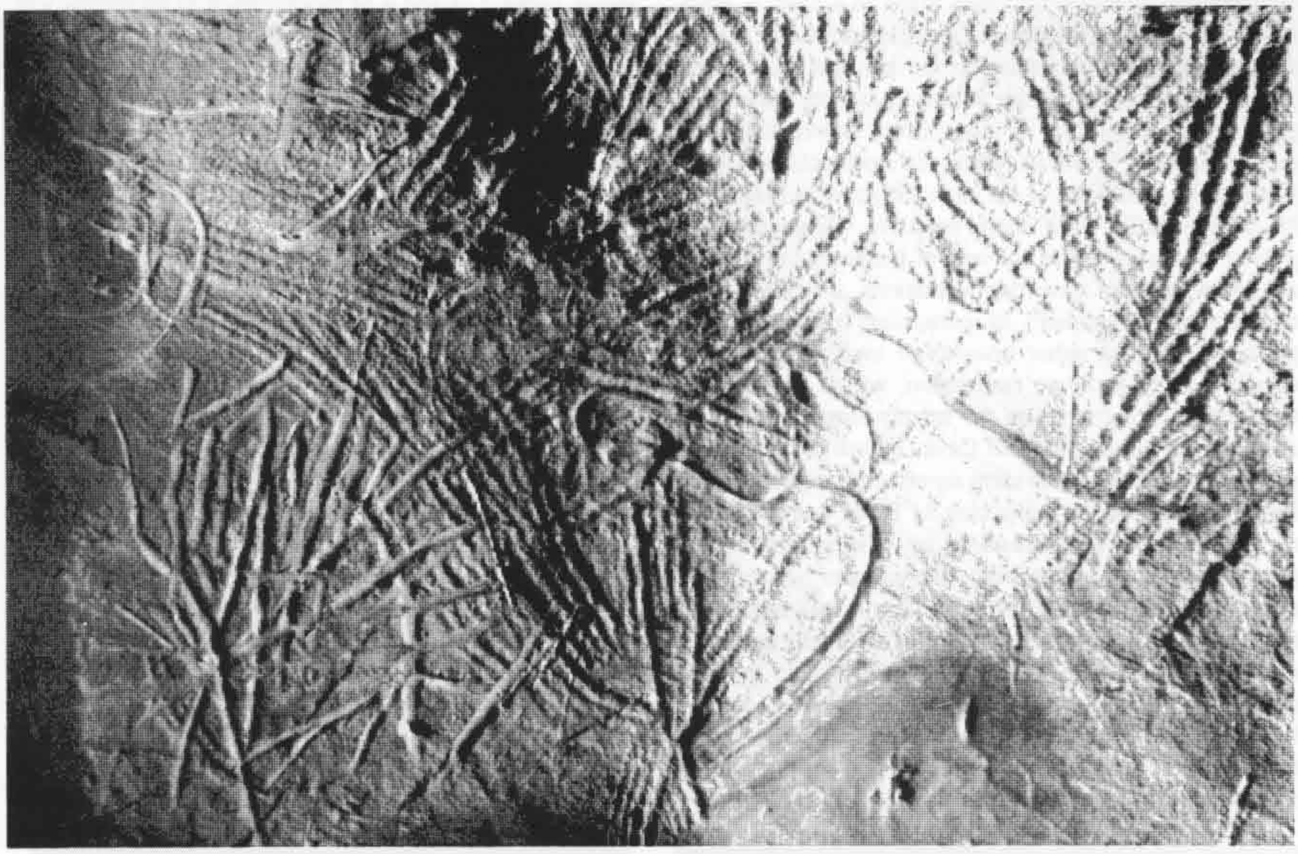

Figure 7. Corroded but otherwise perfectly preserved finger flutings, with superimposed and much fresher, further Palaeolithic rock art. Baume Latrone, France.

surfaces indicates that gravity is involved in the precipitation process. The dominant mechanism in the formation of these **exudations** appears to be that of selective deposition along ridges, as described above (Figure 5-5; see also Figures 2, 4).

Surface modification and the speleoclimate

What may one deduce from these different modification phenomena?

Type 1, the least altered state, is usually restricted to deep and extensive cave systems: Rouffignac, Grotte du Cheval at Arcy-sur-Cure, Montespan, Baume Latrone (all France), Koonalda Cave, Nung-kol Cave (both Australia) and Kalate Egeanda (Papua New Guinea). My speleoclimatic work has shown that these are least susceptible to air convection, either in or out of the cave, and have a high and stable air humidity. New Guinea 2 Cave (Victoria) seems to suggest that the latter is the more decisive factor because this cave is somewhat smaller and comparatively unprotected against convection, yet maintains a high humidity (98%) even through the peak of summer. However, one must be cautious in drawing inferences from this site; it contains a rivulet, and its ceiling precipitates comprise large proportions of material apparently deposited in the crystal interstices (colloids and fine sand fractions) — one would need to know how much this has caused the stabilisation of the migratory carbonates before accepting this cave's geomorphological indices.

Precise measurements at one of the best-preserved finger fluting sites, Baume Latrone (Gard, France) (Figure 7), indicate an extremely stable climatic environment: rock and air temperatures were found to be closely allied (the discrepancy never exceeded 0.45°C), and an overall air temperature fluctuation rate of only 0.7°C was detected over a seven-day period even at the test station nearest the entrance (95 m into the cave). Humidity varied throughout the cave, however, ranging from 77.3 to 93.5 per cent during the test period.

At Malangine Cave, the finger-marked deposits are among the most modified calcitic precipitates in the cave (Bednarik 1981a). The climatic regime of that site has been the subject of a particularly comprehensive investigation (Bednarik in prep.) which shows that the site is more susceptible to fluctuations generated by external conditions than are deep caves. This is certainly reflected in the character of the calcitic excrescences. Yet even this cave was found to influence the speleoclimate greatly, particularly in stabilising the thermal environment.

It is beyond my present scope to elaborate in detail on the climatic systems to which the parietal atmosphere may be subjected, and my speleoclimatic studies are still continuing, almost twenty-five years after they were commenced. Nevertheless, it may be appropriate to present some general observations. The degree to which the environment at some particular place in a cave is influenced by external conditions depends primarily on the distance from the entrance, on the configuration of the passages, on the size of the entrance, and on the relative positions of entrances in those caves where there are more than one. In places where the speleoclimate is influenced by proximity to the cave entrance, it is likely to be more volatile, with more intensive evaporation and greater increases in the convective temperature, accelerating deposition of travertine formations, which are more compact and smoother. In particular, rising entrance passages (inclined either towards or away from the entrance) greatly facilitate convection, which may explain the brittle excrescences on the steeply sloping ceiling of such sites as Orchestra Shell Cave (Figure 8). A passage may form a siphon, providing an effective barrier to any heat exchange because a pocket of either warm or cold air will form there (depending on whether the siphon turns upwards or downwards). The climate beyond such an air lock will be quite stable if there is no pronounced air seepage through any rock fissures. Near the entrance, radiant heat is likely to have some influence, but this diminishes rapidly in most caves as one proceeds deeper. It must be noted, however, that many larger cave systems have a strong airflow, which may be subject to changes related to annual seasons.

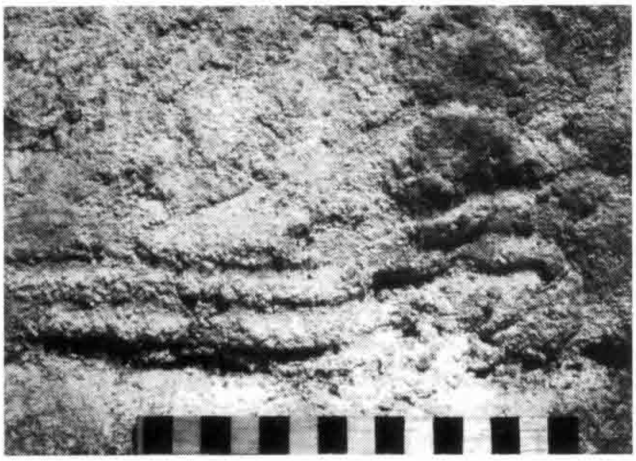

Figure 8. *Finger flutings with subsequent speleothem growths of varying extent. 'Old part' of Orchestra Shell Cave, Western Australia.*

My speleoclimatic work leads me to suggest that both the specific kind of travertine deposited in a cave and the type of modifications to which it is then subjected are determined more by the complex climatic environment within a cave, than by factors related to the composition of the overlying rock, to water pH, moisture availability, chemical impurities, catalysts or similar variables.

In order to appreciate the often complex modification processes that may have a bearing on parietal markings of any type (human or non-human), one needs to have some familiarity with the factors influencing travertine deposition and modification. The logical end result of the continued influence of the processes responsible for the above Types 2, 3 and 4 of modification to travertine will ultimately be a complete masking of finger lines. Once the gaps are filled between the ridges, there is no means of recognising the markings beneath the speleothem skin (other than sectioning). The end result of the Type 5 process is the complete dissolution of the *montmilch*, and the disappearance of the finger flutings (Figure 9).

Figure 9. *The white* montmilch *is being dissolved progressively, and where it was once marked by fingers it has disappeared completely. Koongine Cave, South Australia.*

Even the Type 1 process must eventually result in the complete destruction of the rock art, because the ridges between individual grooves are worn at a much greater rate. This raises the taphonomic question: in how many instances have finger lines been completely obliterated and can no longer be detected? We can only conjecture about the number of sites where the former petroglyphs are either totally covered by later speleothems, or have been completely worn away by kinetic or chemical erosion. A positivistic line of enquiry cannot effectively deal with such questions, which renders it superfluous in archaeology: all of that discipline's pronouncements are entirely predicated on taphonomy. Even the apparent restriction of finger fluting sites to certain regions of western Europe and southern Australia need not necessarily be an indication of the former distribution and extent of this ancient tradition; the geographical occurrence may not be archaeologically significant. Unless we can convincingly establish that it is not due to those climatic and geological factors which are crucial to the survival of the delicate medium of the finger flutings, the *montmilch* deposits, it is much more likely that today's distribution of this phenomenon is a taphonomic effect. (In using the term taphonomy I merely follow established archaeological terminology; I would prefer to substitute the more comprehensive and more correct word 'metamorphology'; Bednarik 1995.)

Characterising finger fluting sites

Let us now turn to consider the characteristics that finger fluting sites have in common. Some of these are self-evident: such sites must be limestone caves accessible to pre-Historic people, and located in a region populated by them. Obviously, the caves must have contained soft deposits suitable for marking at that time. Not so obvious as a common characteristic, but possibly of significance, is that several of these sites feature seams of sedimentary silica which, at least in seven of the caves, have been mined by pre-Historic people (Bednarik 1980, 1986b, 1990b, 1992; Aslin and Bednarik 1984). Traces of mining at Gran Gran Cave (South Australia) were recognised (Luebbers 1978: 107-8) before our discovery of the petroglyphs there. The extensive mining in Koonalda Cave was reported earlier still (Gallus 1968), but in Europe, subterranean Palaeolithic chert mining was not recognised until 1981 (Bednarik 1986b).

Silica seams are not a feature common to all the sites with finger flutings, but another characteristic is much more universal: nearly all these caves have a distinctly thin roof. At many of the sites in question, the roof thickness never exceeds three metres, and a thickness of twenty metres is exceeded only rarely. It could be argued that this is not surprising in the Tertiary karst plains of southern Australia, where roofs generally tend to be rather thin. However, the distinction is particularly conspicuous in the Dordogne and in Lot, France, where all of the caves concerned are located just below the ridges or plateaus of the hills; none of the abundant caves of the valleys contains such markings, but practically all were heavily occupied in the Upper Palaeolithic and many contain *montmilch* deposits. The few similarly marked caves elsewhere in Europe (in the Provence, Gard, Yonne, the French Pyrenees, and Cantabria in Spain) also comply with this rule: even very extensive systems with finger flutings are generally near the surface and have a comparatively thin roof (Bednarik 1986a). Of the European sites I have examined, Grotte du Cheval has the thickest roof, about twenty-two metres, but it has only engraved *montmilch* and lacks actual finger markings. Cosquer Cave, one of the largest European sites with finger flutings (Clottes et al. 1992), has a roof thickness of about fifty metres, but having been partially submerged during the entire Holocene it can be expected to have an unusual hydrology and speleoclimate.

Of the thirty-one known Australian sites of finger flutings in 1990 (Bednarik 1990a; more are known now), thirty also have very thin roofs, the clear exception being New Guinea 2 Cave (Figure 10). However, it may be more than a coincidence that this also happens to be the only site investigated with a stream and where the finger fluting medium is not pure, white *montmilch*.

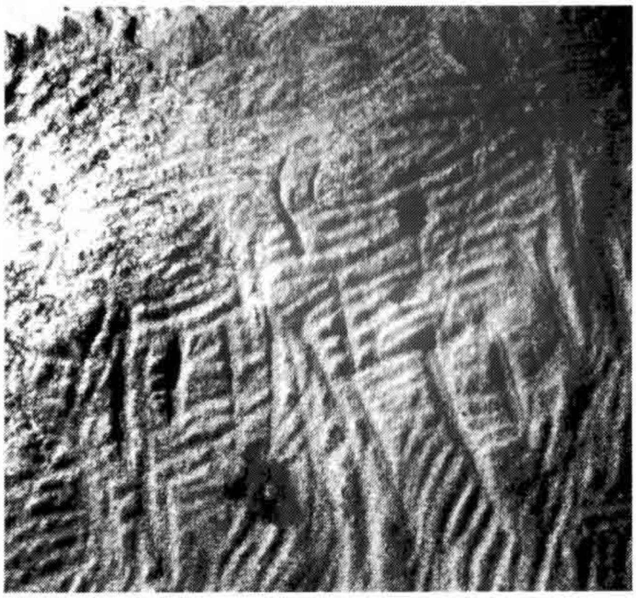

Figure 10. *Finger flutings and tool marks in New Guinea 2 Cave, eastern Victoria. The stippled appearance of this* montmilch *is attributable to fluvial deposition of colloids and fine sand in its interstices.*

It seems reasonable to suggest that the thinness of a cave roof, that is, the proximity of the precipitate to the source of biological carbon dioxide, is somehow related to the formation of the type of *montmilch* deposits that are most likely to facilitate the survival of artificial markings. Nevertheless, an alternative interpretation may be more plausible: the survival of the rock art is perhaps best assured in a cave that is either not a particularly prolific producer of *montmilch*, or where the speleothem growth subsided soon after the finger markings were made. The exact relationship depends on determining the crucial common denominator of the phenomenon category (Bednarik 1990-91), and I regard the issue as only partly clarified. Distance from the surface above is a key factor facilitating both the precipitation of suitable deposits, and the long-term survival of any finger flutings. The survey of all sites in southern Australia has established that the most favourable zone is from about two metres to six metres below the surface. Both above and below this zone, suitable deposits as well as surviving markings are exceptionally rare. This observation is important not only for scientific purposes and taphonomic considerations, but also for matters relating to questions of preservation.

The palaeoclimatic significance of parietal travertines

Many types of components of caves are excellent indicators of palaeoclimatic conditions and oscillations. The potential of floor sediments is well appreciated in this respect, particularly in European Quaternary research, but valuable information may also be provided by speleothems. The most common speleothems, the carbonates, are usually formed during periods of dense vegetation on the surface above the cave. The carbon dioxide required to transport the carbonates is largely of biological origin, and is derived in most cases from the humus layer; exceptions are in areas with volcanic activity, and where there is humic acid in Rendsina horizons above the cave (Bögli 1960).

The correlation between parietal travertines and major climatic fluctuations has been the subject of intensive investigation in Europe (Lais 1940; Geyh and Schillat 1966; Franke 1967; Labeyrie et al. 1967). Regions experiencing extensive denudation of the tree cover during glacial peaks, for example much of central Europe, lack practically any travertine formation from the cold periods (Geyh 1970). The extensive statistical work of Franke and Geyh (1970) failed to find any between about 12 000 and 20 000 years BP, and found only a low occurrence for the period of 25 000 to 32 000 years BP, that is, for the last and penultimate stadials. In southern Europe, carbonate speleothems are common, but they are still lacking from the second half of the final Würm stadial which is often described as particularly severe.

The contention of some karst morphologists that the solubility of carbon dioxide increases with lower temperatures is inapplicable here; firstly, because cryocratic periods would presumably have also affected the speleo-atmospheric temperatures, thus compensating for any solubility increase; and secondly, because such an increase would have little effect during a period of significantly decreased carbon dioxide production. Atmospheric carbon dioxide levels were lower during glacial periods, as we know from ice cores in Antarctica and Greenland (Morgan 1993). In addition, lower moisture availability would have further inhibited speleothem growth, at least during stadial peaks (which were not only cold, but also very dry).

Travertine formation in a cave generally proceeds intermittently. Whilst the above studies by Franke and Geyh are based on radiocarbon dating, there are relative ways of dating stalactitic material. For example, flowstone or stalagmites may be submerged under datable sedimentary strata, or they may rest on an horizon which predates the time of the speleothem precipitation. Geyh and Franke make two interesting observations in Europe. Stalagmites (in radiocarbon dating work they are preferred to stalactites, which often grow much faster and have more complex structures) formed during the Holocene had a growth rate approximately ten times that of those from Würm interstadials; and there appears to be a complete lack, at least in central Europe, of stalagmites containing material from both the Holocene and any earlier temperate or warm period. Yet the duration of growth, without there being a translocation of the drip point, has been found to range over a few tens of millennia. As a consequence it is suggested that stadials have affected the hydrological systems responsible for the selection of drip point sites (Franke and Geyh 1970: 3).

The intermittent nature of dripstone formation is frequently evident in caves. Distinct generations can often be discerned, including white or semi-translucent 'active' forms, and fossil stalagmitic deposits in varying stages of deterioration. Holocene dripstone is completely lacking in the high altitude caves of the European Alps, which contain only Pleistocene travertine. Low altitude caves often have little speleothem growth from the Holocene (Cougnac, Lot, is a good example), but may contain massive formations from the Last Interglacial. On the other hand, caves which have been modified by fluvial action up until the early Würm have only Holocene carbonate speleothems. For example, they are very sparse in the Gudenus Cave (Austria), last inundated between two Middle Palaeolithic levels, where they occur only above the Magdalenian floor (Bednarik 1994b); in Trilobite Cave (Yonne, France), last flooded between the Mousterian and the Gravettian levels, they are restricted to above the sediments, which is also the case in the Promenadensteighöhle (Lower Austria; Bednarik 1970). The same separation is demonstrated in Baume Latrone (Bednarik 1986a).

Figure 11. *Fossil and stabilised* montmilch *with modified finger flutings, over which more recent, white speleothem has been deposited. Croze à Gontran, France.*

A reprecipitated calcite sequence of particular interest is found in Croze à Gontran (Figure 11). The primary limestone is corroded, brown and covered by a grey deposit of cutaneous travertine, a former *montmilch* that was later stabilised. A variety of dense deposits covers it in places, while elsewhere smaller patches of clearly more recent soft *montmilch*, pure-white and apparently still 'active', are found. The finger flutings at this site are restricted to the older of the two speleothem generations; there are instances of finger grooves which have been filled in completely and covered by the subsequent white deposit. In view of the abundant evidence elsewhere which suggests a correlation between the travertine and periods of climatic amelioration, it may be that the more recent *montmilch* is of the Holocene (hardly a contentious claim), and that the preceding generation of secondary calcite, as well as the exudations on it, date either from the major Würm Interstadial (Göttweig) or from the Eem Interglacial. The extensive older deposits would have required quite favourable environmental conditions (vegetation cover, atmospheric precipitation and temperature). This chronological interpretation coincides with the antiquity credited to these petroglyphs, which also include iconic representations: archaeologists believe that they date from the Aurignacian, a tool tradition of the Göttweig (Sieveking and Sieveking 1962).

The sequence in Croze à Gontran is surprisingly similar to that of Malangine Cave. Here, too, the finger-marked, fossil *montmilch* has experienced such modification. A large ceiling area in the north-west of the first-mentioned cave bears a second generation of *montmilch*, pure-white and downy, still active and evidently of the Holocene. This deposit is superimposed over the earlier precipitate and over the flutings fashioned in it. There is no reason to assume that this sequence should not be related to climatic factors, but the nature of these has yet to be better established in Australia.

Carbonate speleothems are thus sensitive palaeoclimatic indicators, and are important to dating attempts where the medium of petroglyphs happens to be a speleothem. In Europe, the growth rates, duration of growth, and — within limits — the age of stalagmites have been determined for a large number of samples by establishing the radiocarbon contents of the precipitates. Often growth rates can be checked by a method similar to dendrochronology, because some stalagmites and pearly travertines possess minute laminations caused by annual variations in growth, presumably also related to climatic oscillations (Homann 1969; Geyh and Franke 1970). Baker et al. (1993) have shown, using high-precision thermal-ionisation mass-spectrometry ^{238}U-^{234}U-^{230}Th dating, that the luminescence banding in speleothems is indeed annual. Thus reprecipitated calcite has a potential for relative dating, in addition to that by radiometric means (uranium series and radiocarbon), due to its geomorphological character: cave travertines require the presence of a reasonably dense vegetation above the cave, and this can in turn be related to particular climatic conditions. Moreover, as we shall see below, the composition of such speleothems can also permit deductions about the type of plant cover responsible for the carbon dioxide involved in their formation.

Speleothems at Mt Gambier rock art sites

In 1980 I located a sequence of travertine deposits interstratified with a sequence of petroglyphs in Malangine Cave, in the Mt Gambier karst region. The art series seems to commence with *montmilch* finger flutings, followed by deeply carved, apparently non-iconic motifs (I consider their identification as bird tracks subjective). In the southern part of the cave, the latter generation of rock art precedes the main travertine deposit, itself bearing shallow line figures which were executed shortly before the deposit matured. Digital fluting occurs mostly in the deeper parts of both Malangine Cave and nearby Koongine Cave, but there are some instances of superimposition by later petroglyphs. The petroglyph generations in Malangine Cave are thus sandwiched between laminae of speleothem deposits, as indeed they are at several other sites: in Croze à Gontran as reported above, and in the Australian sites Prung-kart (Bednarik 1998b), Nung-kol and Kriton Caves (Figure 12).

Figure 12. *Extensively modified finger flutings in a fossil* montmilch *are crossed over and covered by a series of active, small stalactites. Kriton Cave, western Victoria.*

Identification of the finger flutings as the oldest petroglyph element present in these sites, although adequately resolved by the speleothem stratigraphy, finds support in the complete lack of finger markings on the surfaces exposed by the ceiling collapse in Koongine Cave (which also truncated the *montmilch* panels), which appears to provide a convenient *terminus ante quem* for the petroglyph production in that cave. The collapsed mass of rock was buried under some one or two metres of sediment (now mostly removed by guano mining), and its lower portions may still bear traces of rock art (Bednarik 1989). If a datable occupation floor could be located beneath the rock fall it would provide a maximum date for the roof fall, and help in establishing the minimum age of the finger flutings. Other evidence relating to the minimum age of the art are the floor sediment deposits that sometimes conceal the lower part of the decorated areas, or that have rendered human access to them impossible. This can be observed in Koongine Cave (on the east wall), as well as in other sites, such as Malangine Cave (east wall) and Orchestra Shell Cave (new part). In Yaranda Cave megafaunal scratch marks (claw spacings in excess of 35 mm) postdate the finger flutings by a substantial time span.

The relative chronological framework attempted for the petroglyphs, calcite deposits, sediments and associated lithic assemblages in Malangine Cave (Figure 13) was the first application of direct dating of rock art in the world (Bednarik 1981a, 1981b, 1984, 1993: Fig. 1). Almost one half of the carbon contained in carbonate speleothems is derived from the atmosphere, and in most environments from respired carbon dioxide. The ^{14}C so included in reprecipitated carbonates (be they speleothems or pedogenetically derived accretions; Bednarik 1980) then decays at the known rate, enabling conventional or AMS radiocarbon analysis of such deposits.

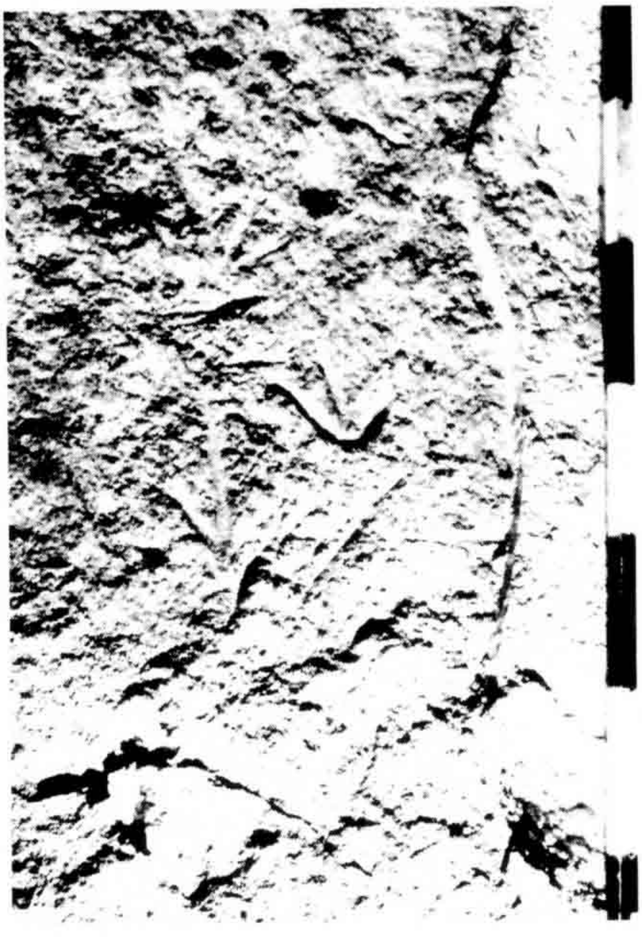

Figure 13. *Laminar cutaneous ceiling travertine, seen on the right, bearing mostly shallow petroglyphs on its surface, while itself covering an earlier generation of deeply carved petroglyphs which are exposed where the deposit has become exfoliated. Malangine Cave, South Australia. (Scale in dm.)*

The ratio of carbon isotopes in reprecipitated carbonates is rather complex. To render the limestone soluble, an excess of carbon dioxide is necessary, causing less then fifty per cent of the bicarbonate's carbon to be derived from the carbonate, and thus be practically ^{14}C free. The method of estimating the proportion of ^{14}C that should have been precipitated in a travertine at the time of its formation was conceived by Franke (1951a, 1951b) only shortly after Libby et al.'s (1949) inauguration of the radiocarbon method. Subsequent research (Franke and Geyh 1970; Franke et al. 1958; Geyh 1969; Hendy 1969) suggests an encouraging reliability for samples from stalagmites; the duration of growth can be determined with great precision. Absolute ages have been obtained of up to 45 000 years, but they are burdened with a potential error because the initial ^{14}C concentration is not derived from the atmospheric $^{14}C/^{12}C$ ratio alone. It is clear from reaction (1) above that a surplus of carbon from the atmosphere is necessary, and while this surplus may theoretically be up to one hundred per cent (equivalent to an error of about 5000 years!) the carbon content in natural bicarbonate solutions ranges only from seventy to eighty per cent, equivalent to an error of less than 1500 years. Even this can be diminished dramatically if the $^{14}C/^{12}C$ ratio in the modern vadose water is determined.

However, there are still other qualifications. The most serious is the infiltration of younger vadose solution and the interstitial deposition of further calcite in the crystal lattice of the speleothem, with the resulting alteration of isotopic ratio. This possibility was initially appreciated by the European investigators, but as they limited their work to dense, crystalline stalagmites, it had little or no effect on their results. Unfortunately nearly all of the secondary carbonate deposits that can be related to rock art, be they speleothems or pedogenetic precipitates, are decidedly porous and therefore invite such deposition, and the rejuvenation it involves. In fact, we know with certainty that many of the former *montmilch* bearing finger flutings became later fossilised through calcification, which means that any radiocarbon age derived from such material is effectively a minimum age, and probably quite conservative.

Another qualification refers to the past isotopic composition of atmospheric carbon, considering that plant communities have a significant effect on the $\delta^{13}C$ value of the reprecipitated carbonate: values of between -12‰ and -10‰ apply to respiratory carbon dioxide derived from C3 plants, while the $\delta^{13}C$ compositions of carbonate in equilibrium with carbon dioxide respired from C4 plants range from -3‰ to +1‰ (Cole and Monger 1994). C4 plants, so called because of the four-carbon acids as which carbon dioxide is initially captured in their outer mesophyll cells, include about half of the world's grasses, which have a physiological advantage over C3 plants in low atmospheric carbon dioxide concentrations (Robinson 1994). The latter are directly related to world climate, and were significantly lower during the Pleistocene glacials, as noted above. This introduces yet another variable, the effect of which is an unknown factor and questions the utility of all uncalibrated Pleistocene radiocarbon dates.

These considerations are only some of those that should temper our sometimes blind reliance on scientific data. In the case of radiocarbon dating, there are others, some of which I have rehearsed elsewhere, including those of the relevant statistical constraints (Bednarik 1994c). To test the proposition of isotopic rejuvenation through calcification, and at the same time obtain the first direct data for the age of the rock art in Malangine Cave, two samples from that site were analysed for their isotopic carbon composition in 1980. One was from the laminated and comparatively dense ceiling travertine that separates the two basic art traditions present near that site's entrance (Figure 13). It yielded an adjusted age of 5550 ± 55 years BP (Hv-10241) which might best be described as a very conservative *minimum mean age* for the entire lamina. Cutaneous speleothems of this type require substantial time spans for their formation and, assuming a minimal post-depositional rejuvenation from younger solute, precipitation would have commenced some time before 6000 BP, which would provide a conservative minimum age for the deep petroglyph generation. It may be relevant that 'absolute' radiocarbon ages for several occupation deposits in the coastal region of south-eastern South Australia are from the early Holocene (Tindale 1957: 110; Luebbers 1978: 113-34), and therefore coincide in their magnitude with the implied age of the pre-lamina petroglyphs in Malangine Cave. Also pertinent may be the results of a later excavation of Koongine Cave, just 105 metres to the west of Malangine, which yielded a series of radiocarbon dates from sedimentary charcoal that is thought to have been introduced by human occupation (Frankel 1986). There is a concentration of early Holocene dates evident, and while this may not reflect archaeological reality or even relate to the human presence demonstrated by the rock art, there is a possibility that some of the art of the two caves was created during that apparent occupation phase. However, a uranium-series date from the same lamina sample in Malangine Cave was 28 000 ± 2000 years BP (Bednarik 1997), which, if valid, suggests a massive distortion by rejuvenation of the material. It would also indicate that the U/Th ratio was probably not rejuvenated.

The second sample processed was from the pearly travertine in the deep part of Malangine Cave, where it clearly postdates the finger flutings (Figure 14). The radiocarbon age of 4425 ± 75 years BP (Hv-10240) compares very well with the uranium-series result from the same sample, of 4300 ± 500 years BP, overlapping it comfortably at one sigma.

More recently, another site, about 31 kilometres from Malangine Cave, was subjected to a similar study. In Prung-kart Cave, finger flutings have been preserved under a laminar speleothem of 15 to 20 millimetres thickness (Figure 15). After the natural exfoliation of almost one square metre of this deposit, caused by the fine rootlets of an exotic tree species (*Pinus radiata*), it was found that the cutaneous travertine consists of over a dozen distinctive laminae in section. They are alternatively white and grey layered and it was hoped that the darker layers had been caused by the deposition of organic matter during periods of higher aquifer levels.

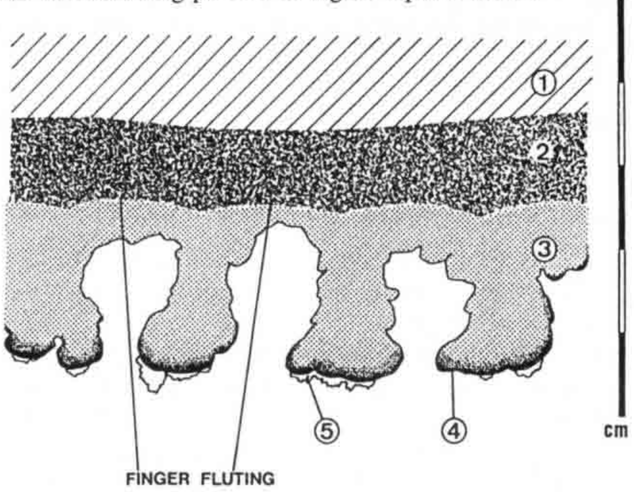

Figure 14. *Section of extreme speleothem growth covering finger flutings: 1 - primary rock of cave roof; 2 -* montmilch, *bearing finger fluting; 3 - pearly exudations of carbonate speleothem, the arrangement of which reflects that of the finger flutings; 4 - brown organic stain, partly interstitial and concentrated on the lowest surfaces; 5 - yellowish-white efflorescence of sulphates.*

Figure 15. *The cutaneous speleothem seen on the left has exfoliated on the right, exposing the primary rock. The laminar deposit contains within it finger flutings, the course of which remained visible on the most recent surface of the deposit. Northern passage, Prung-kart Cave, South Australia.*

ASL Sample	Mass, g	Lab No.	$\delta^{13}C$, ‰	^{14}C, % mod.	$d^{14}C$, ‰	$D^{14}C$, ‰	^{14}C age, years BP
142018	51.28	Hv-10240	+0.2	57.7 ± 0.5	-	-	4425 ± 75
142035	c. 400	Hv-10241	-4.8	50.1 ± 0.3	-	-	5550 ± 55
188004 (a)	118.5	ANU-6963A	-5.0 ± 2.0	-	-245.8 ± 6.0	-276.0 ± 6.5	2590 ± 80
188004 (aa)	recalcul.	ANU- 6963	-0.8 ± 0.1	-	-245.8 ± 6.0	-282.2 ± 5.7	2660 ± 70
188004 (b)	split	ANU- 6963B	-5.0 ± 2.0	-	-97.4 ± 8.3	-133.5 ± 8.8	1150 ± 80
188013	65.8	ANU- 8457	-1.1 ± 0.1	-	-272.4 ± 5.9	-307.2 ± 5.6	2950 ± 70

Table 1. *Analytical data referred to in the text. Notes: before processing, surface material was removed from all bulk samples in the laboratory. There was no chemical pretreatment.*

Since the finger flutings are sandwiched within this laminar deposit, it was separated into inner (older) and outer (younger) layers, and isotopic carbon was determined. The outermost portion of the travertine skin produced a radiocarbon age of 1150 ± 80 years BP (ANU-6963B), the innermost was 2590 ± 80 BP (ANU-6963A). The dark substance, unfortunately, did not contain adequate organic matter for conventional radiocarbon dating, and accelerator mass spectrometry dating was not attempted.

The age of ANU-6963A was recalculated as ANU-6963, at 2660 ± 70 BP, by basing the calculation on a measured $\delta^{13}C$ of -0.8 ± 0.1‰, not the estimate normally used in routine calculations (-5.0 ± 2.0‰). A further sample from the inner strata then yielded a date of 2950 ± 70 BP, $\delta^{13}C$ being -1.1 ± 0.1‰ this time (ANU-8457). The measured deviations of ^{13}C from that of standard marine limestone carbon are lower than was estimated, and much lower than in atmospheric carbon dioxide. This could suggest that the carbon active in the travertine skin formation derives almost entirely from inorganic sources (gaseous volcanic emissions), or alternatively from C4 plants. The Mt Gambier region has been subjected to much recent volcanic activity, peaking apparently during the mid-Holocene (Blackburn 1966; Sheard 1983; Prescott 1994), and its Oligocene and lower Miocene limestones are highly porous (Bednarik 1991c reports up to 50.8% volumetric porosity from Paroong Cave). The retention of gaseous cave deposits may well be facilitated by the aquifer level of the region which is frequently close to the surface (Holmes and Waterhouse 1983). For comparison, the measured $\delta^{13}C$ of the two samples of speleothem in Malangine Cave was +0.2‰ (Hv-10240) and -4.8‰ (Hv-10241) (Bednarik 1981a), which suggests considerable fluctuation in the region.

The Prung-kart speleothems remain so porous that, without independent calibration (e.g. through organic matter deposited in the layers, or by uranium-thorium dating), it remains unknown how much of the deposit's crystal lattice actually predates the rock art. While the layers found above the art must postdate it entirely, a certain proportion of the travertine beneath the art may still be younger than the art. Hence radiocarbon analysis would provide only minimum values of real age, from both deposits. On the other hand, if a part of the carbon dioxide in the solution process was not of atmospheric, but of volcanic origin, as may be the case, then the dating results are likely to overestimate the age of the calcite formation by an unknown factor. In reality, the carbon dioxide may have been derived from both sources (volcanic and biological), and the relative proportions may have fluctuated through time in accordance with such factors as volcanic activity, aquifer level, ambient climate, vegetation regimes and so forth.

Conclusion

These considerations show us how unlikely it is that reliable dating of such travertine deposits can be obtained by simple radiocarbon determination alone. Similarly, oxygen isotope analysis is not a secure means of determining formation temperature, because the level of ^{18}O in the calcite precipitated is not a function of temperature alone; it can be influenced by kinetic isotopic fractionation. Nevertheless, both the results obtained from radiocarbon dating of reprecipitated calcite and the heuristic developments it facilitates are a significant help in attaining a better understanding of the complex world of carbonate speleothems. They may not provide us with finite answers concerning the rock art such phenomena may spatially be associated with, but they certainly help us better to focus on the issues and complex interrelationships. They also open up new and better avenues of future research in this complex area. I find some of the possibilities foreshadowed here most exciting. For instance, the mechanisms determining the interrelationships between atmospheric carbon dioxide levels and temperatures, vegetation patterns, isotopic fractionation (and thus radiocarbon ages) and past climates can now be subjected to new scrutiny. If, as the Antarctic ice cores suggest, there is a solid correlation between climate and carbon dioxide level, and another between carbon dioxide level and respired $\delta^{13}C$, by way of favoured plant communities, how does this affect uncalibrated radiocarbon dates? And how much influence could plant communities have on atmospheric temperature? These are contentious issues, and they are very weighty indeed. I hope to have shown in this paper that carbonate speleothems, themselves such exceedingly complex phenomena, are among those that can play a role in the future investigation of such important issues — issues that are not only relevant to archaeologists and rock art students, but to the human understanding of the macro-ecology of the global environment.

Acknowledgments

The help of Professor M. A. Geyh, Dr Andrée Rosenfeld, Dr M. John Head, Geoffrey D. Aslin and Elfriede K. Bednarik is gratefully acknowledged. Many thanks also to the *Artefact* referees.

Robert G. Bednarik
International Institute of Replicative Archaeology
P.O. Box 216
Caulfield South, Victoria 3162
Australia

REFERENCES

ASLIN, G. D. and R. G. BEDNARIK 1984. Karlie-ngoinpool Cave: a preliminary report. *Rock Art Research* 1: 36-45.

BAKER, A., P. L. SMART, R. LAWRENCE EDWARDS and D. A. RICHARDS 1993. Annual growth banding in a cave stalagmite. *Nature* 364: 518-20.

BALLARD, C. 1993. First report of digital fluting from Melanesia. *Rock Art Research* 9: 119-21.

BEDNARIK, R. G. 1965. Arbeitsbericht über das Gebiet der Schneealpe. *Höhle und Spaten* 1: 55-9.

BEDNARIK, R. G. 1970. Die Grabungen in der Promenadensteighöhle (1961-1964). *Die Höhle* 21: 117-26.

BEDNARIK, R. G. 1980. The potential of rock patination analysis in Australian archaeology — part 2. *The Artefact* 5: 47-77.

BEDNARIK, R. G. 1981a. Malangine and Koongine Caves, South Australia. Unpubl. MS, 38 pp., Archive of the Australian Rock Art Research Association, Melbourne.

BEDNARIK, R. G. 1981b. Finger lines, their medium, and their dating. Unpubl. MS, 34 pp., Archive of the Australian Rock Art Research Association, Melbourne.

BEDNARIK, R. G. 1984. Die Bedeutung der paläolithischen Fingerlinientradition. *Anthropologie* 23: 73-9.

BEDNARIK, R. G. 1985. Parietal finger markings in Australia. *Bollettino del Centro Camuno di Studi Preistorici* 22: 83-8.

BEDNARIK, R. G. 1986a. Parietal finger markings in Europe and Australia. *Rock Art Research* 3: 30-61, 159-70..

BEDNARIK, R. G. 1986b. Cave use by Australian Pleistocene man. *Proceedings, University of Bristol Speleological Society* 17: 227-45.

BEDNARIK, R. G. 1987-88. The cave art of Western Australia. *The Artefact* 12: 1-16.

BEDNARIK, R. G. 1989 Perspectives of Koongine Cave and scientistic archaeology. *Australian Archaeology* 29: 9-16.

BEDNARIK, R. G. 1990a. The cave petroglyphs of Australia. *Australian Aboriginal Studies* 1990(2): 64-8.

BEDNARIK, R. G. 1990b. About Pleistocene chert mining. *Sahara* 3: 113-5.

BEDNARIK, R. G. 1990-91. Epistemology in palaeoart studies. *Origini* 15: 57-78.

BEDNARIK, R. G. 1991a. On natural cave markings. *Helictite* 29(2): 27-41.

BEDNARIK, R. G. 1991b. Comment on F. d'Errico, 'Microscopic and statistical criteria for the identification of prehistoric systems of notation'. *Rock Art Research* 8(2): 89-91.

BEDNARIK, R. G. 1991c. The Paroong Cave Preservation Project. In C. Pearson and B. K. Swartz (eds), *Rock art and posterity: conserving, managing and recording rock art*, pp. 66-70. Occasional AURA Publication 4, Australian Rock Art Research Association, Melbourne.

BEDNARIK, R. G. 1992. Early subterranean chert mining. *The Artefact* 15: 11-24.

BEDNARIK, R. G. 1993. The calibrated dating of petroglyphs. *The Artefact* 16: 32-8.

BEDNARIK, R. G. 1994a. The discrimination of rock markings. *Rock Art Research* 11(1): 23-44.

BEDNARIK, R. G. 1994b. Pedogenetic dating of loess strata. Paper presented to Fifth Australian Archaeometry Conference, Armidale (in press).

BEDNARIK, R. G. 1994c. Conceptual pitfalls in Palaeolithic rock art dating. *Préhistoire Anthropologie Méditerranéennes* 3: 95-102.

BEDNARIK, R. G. 1995. Metamorphology: in lieu of uniformitarianism. *Oxford Journal of Archaeology* 14: 117-22.

BEDNARIK, R. G. 1998a. Microscopic analysis of 'engraved plaques' and other objects from Devil's Lair. *Journal of the Royal Society of Western Australia* 81: 165-75.

BEDNARIK, R. G. 1998b. Direct dating results from Australian cave petroglyphs. *Geoarchaeology* 13: 411-18.

BLACKBURN, G. 1966. Radiocarbon dates relating to soil development and volcanic ash deposition in southeast South Australia. *Australian Journal of Science* 29: 50-2.

BÖGLI, A. 1960. Kalklösung und Karrenbildung. *Zeitschrift für Geomorphologie* 2: 4-21.

BREUIL, H. 1952. *Four hundred centuries of cave art*. Centre d'Études et de Documentation Préhistoriques, Montignac.

CLOTTES, J., J. COURTIN and H. VALLADAS 1992. A well-dated Palaeolithic cave: the Cosquer Cave at Marseille. *Rock Art Research* 9: 122-9.

COLE, D. R. and H. C. MONGER 1994. Influence of atmospheric CO_2 on the decline of C4 plants during the last deglaciation. *Nature* 368: 533-6.

CRAIG, H. 1953. The geochemistry of the stable carbon isotopes. *Geochimica et Cosmochimica Acta* 3: 53-92.

FRANKE, H. W. 1951a. Altersbestimmung an Sinter mit radioaktivem Kohlenstoff. *Die Höhle* 2: 62-4.

FRANKE, H. W. 1951b. Altersbestimmungen von Kalzitkonkretionen mit radioaktivem Kohlenstoff. *Die Naturwissenschaften* 38: 527-31.

FRANKE, H. W. 1967. Isotopenverhältnisse in sekundärem Kalk — geochronologische Aspekte. *Atompraxis* 13: 1-11.

FRANKE, H. W. and M. A. GEYH 1970. Isotopenphysikalische Analysenergebnisse von Kalksinter — Überblick zum Stand ihrer Deutbarkeit. *Die Höhle* 21: 1-9.

FRANKE, H. W., K. O. MÜNNICH and J. C. VOGEL 1958. Auflösung und Abscheidung von Kalk — C^{14}-Datierung von Kalkabscheidungen. *Die Höhle* 9: 1-5

FRANKEL, D. 1986. Excavations in the lower southeast of South Australia: November 1985. *Australian Archaeology* 22: 75-87.

GALLUS, A. 1968. Parietal art in Koonalda Cave, Nullarbor Plain, South Australia. *Helictite* 6(3): 43-9.

GEYH, M. A. 1969. Isotopenphysikalische Untersuchungen an Kalksinter, ihre Bedeutung für die ^{14}C-Altersbestimmung von Grundwasser und der Erforschung des Paläoklimas. *Geologisches Jahrbuch* 88: 149-58.

GEYH, M. A. 1970. Zeitliche Abgrenzung von Klimaänderungen mit ^{14}C- Daten von Kalksinter und organischem Ma-

terial. *Geologisches Jahrbuch* 89: 123-38.
GEYH, M. A. and H. W. FRANKE 1970. Zur Wachstumsgeschwindigkeit von Stalagmiten. *Atompraxis* 16: 85-101.
GEYH, M. A. and B. SCHILLAT 1966. Messung der Kohlenstoffisotopenhäufigkeit der Kalksinterproben aus der Langenfelder Höhle. *Der Aufschluss* 17: 315.
HALLAM, S. J. 1971. Roof markings in the 'Orchestra Shell' Cave, Wanneroo, near Perth, Western Australia. *Mankind* 8: 90-103.
HENDY, C. H. 1969. The use of C-14 in the study of cave processes. In *Proceedings of the XIIth Nobel Symposium, Uppsala 1969*, pp. 419-43. University of Uppsala.
HENDY, C. H. 1971. The isotopic geochemistry of speleothems. *Geochimica et Cosmochimica Acta* 35: 801-24.
HOLMES, J. W. and J. D. WATERHOUSE 1983. Hydrology. In M. J. Tyler, C. R. Twidale, J. K. Ling and J. W. Holmes (eds), *Natural history of the South East*, pp. 49-59. Royal Society of South Australia Inc., Adelaide.
HOMANN, W. 1969. Experimentelle Ergebnisse zum Wachstum rezenter Höhlenperlen. *Fünfter Internationaler Kongress der Speläologie*. Stuttgart.
LABEYRIE, J., J. C. DUPLESSY, G. DELIBRIAS and R. LETOLLE 1967. Étude des températures des climats anciens par la mesure del ^{18}O, du ^{13}C et du ^{14}C dans les concrétions des cavernes. In *Radioactive dating and methods of low-level counting*, p. 153. Proceedings of the IAEA, Vienna.
LAIS, R. 1940. Über Höhlensedimente. *Quartär* 3: 56-108.
LIBBY, W. F., E. C. ANDERSON and J. R. ARNOLD 1949. Age determination by radiocarbon content: world-wide assay of natural radiocarbon. *Science* 109(2827): 227.
LUEBBERS, R. A. 1978. Meals and menus: a study of change in prehistoric coastal settlements in South Australia. Unpubl. Ph.D. thesis, Australian National University, Canberra.
MOORE, G. W. 1952. Speleothem — a new cave term. *National Speleological Society News* 10: 2.
MORGAN, V. 1993. Ice core dating and climatic records. *The Artefact* 16: 8-11.
MILLIMAN, J. D. 1974. *Marine carbonates*. Springer Verlag, New York.
MILLS, G. A. and H. C. UREY 1940. The kinetics of isotope exchange between carbon dioxide, bicarbonate ion, carbonate ion, and water. *Journal of the American Chemistry Society* 62: 1019-26.
PRESCOTT, J. 1994. TL dating of Mt Gambier volcanics. Paper presented to Fifth Australasian Archaeometry Conference, Armidale, Australia (in press).
ROBINSON, J. M. 1994. Atmospheric CO_2 and plants. *Nature* 368: 105-6.
SCHMID, E. 1958. *Höhlenforschung und Sedimentanalyse*. Schriften des Institutes für Ur- und Frühgeschichte der Schweiz 13, Basel.
SCHMID, E. 1963. Cave sediments and prehistory. In D. Brothwell and E. Higgs (eds), *Science in archaeology*, pp. 123-38. Thames and Hudson, London.
SHEARD. M. J. 1983. Volcanoes. In M. J. Tyler, C. R. Twidale, J. K. Ling and J. W. Holmes (eds), *Natural history of the South East*, pp. 7-14. Royal Society of South Australia Inc., Adelaide.
SIEVEKING, A. and G. SIEVEKING 1962. *The caves of France and northern Spain: a guide*. Vista Books, London.
TINDALE, N. B. 1957. A dated Tartangan implement site from Cape Martin, south east of South Australia. *Transactions of the Royal Society of South Australia* 80: 109-23.
WENDT, I., W. STAHL, M. A. GEYH and F. FAUTH 1967. Model experiments for ^{14}C-age determinations. In *Isotopes in hydrology*, p. 321. Proceedings of the IAEA, Vienna.

TA 22-068