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Dating Australian cave petroglyphs

Robert G. Bednarik

Abstract. Modern rock art dating began with the analysis of secondary calcite deposits in an Australian cave that are directly and physically related to petroglyphs sandwiched between them. Since then, further work has been conducted, but has resulted in more questions than answers. This paper summarises the research so far conducted on the isotopic geochemistry of such deposits and the implications for the scientific dating of cave petroglyphs. Caution is advocated in the interpretation of these empirical results and a possible strategy of future research is identified.

Introduction

The cave art of Australia is the world's second largest concentration of rock art that survived either entirely or principally in limestone caves. Although there are pictograms (pigmented rock art) in several caves on the Nullarbor (Lane and Richards 1966) and in three Tasmanian caves (Loy et al. 1990), the bulk of Australian cave art consists of petroglyphs (rock art produced by a reductive method). They have so far been reported from four geographical regions. These are the limestone areas near Perth, the Nullarbor karst plain, the Mt Gambier karst, and a single instance from near Buchan, eastern Victoria (Figure 1). By far the largest concentration so far found is that near Mt Gambier, extending roughly from Millicent in the far south-east of Australia to Portland in western Victoria.

With a few notable exceptions, most of these sites of Australian cave petroglyphs (Bednarik 1990) have only been reported and examined since about 1980. However, the question of their age estimation has been investigated since that same time, and in fact led to the first attempts of direct dating of any rock art in the world. Investigation of the potential of isotopic geochemistry in establishing the antiquity of rock art in limestone caves thus began in 1980.

In a determination of the merits of a geomorphological and geochemical examination of the media of cave petroglyphs, ranging from hammered to abraded markings and finger flutings, of dating clues derived from the materials bearing or concealing this art, we need to acquaint ourselves with the nature of speleothems. Equally important are the effects of modification processes on them, and the significance of different states of preservation. These issues are to be considered here.

Carbonate speleothems

Speleothems (for definition see Moore 1952) result from the responses of particular dissolved rock constituents to atmospheric/hydrospheric conditions in a cave space. They are formations of precipitated compounds such as chlorides (Goede et al. 1992), nitrates, sulphates (James 1991) and, most importantly, carbonates. Calcite, dolomite and aragonite generally form carbonate speleothems. 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. They can also occur as *mondmilch* (*montmilch*, moomilk, *Bergmilch*, etc.; Bates and Jackson 1987; Fischer 1989). The morphology of this form of carbonate speleothem ranges from a dough-like soft mass, over a metre thick and of very high water content, to a sparse white and powdery growth. Consisting usually of comparatively pure calcite deposited in crystal form, the size of the crystals and their mode of arrangement and spacing may differ substantially (Dreybrodt 1988) in different forms of carbonate speleothems. The crystals may be massive and densely packed (as in stalagmites), or they may be very small and widely spaced, rather like the minute water crystals of snow flakes. These deposits are generally precipitated from calcium bicarbonate solution.

The ability of water to hold carbon dioxide in solution is related to factors such as temperature, turbulence and pressure. Pressure changes dramatically when the bicarbonate solution, percolating through gravity, 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 cave space, however, experiences atmospheric pressure and

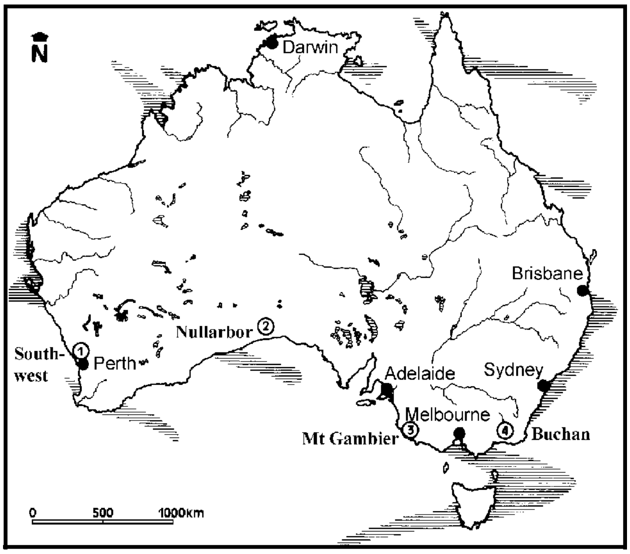

***Figure 1.** The distribution of the four known concentrations of cave petroglyphs in Australia.*

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; Goede et al. 1982; Hendy 1971; Milliman 1974: 7-12).

Carbonate speleothems are sensitive palaeoclimatic indicators (Hendy and Wilson 1968), and are important to dating attempts where the medium of petroglyphs happens to be a speleothem, or where rock paintings, petroglyphs or mining evidence (cf. Bednarik 1995) in caves have become covered by such deposits. In Europe, the growth rates, duration of growth, and—within limits—the age of stalagmites have long 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 formations 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 (cf. Schwarcz 1980; Gascoyne and Schwarcz 1982).

However, 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 stalagmite 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 their 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. A surplus of carbon from the atmosphere is necessary in the reaction. 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.

Two other methods have been used to estimate the time of deposition of calcite speleothems related directly to rock art (Bednarik 2001). One is uranium-thorium analysis, which is one of a group of radiometric or isotopic methods, uranium-series dating. It is based on the decay series of the uranium isotopes to lead. Uranium-238 is by far the most abundant radioactive element in the Earth's crust, consequently its decay products are widely dispersed in the lithosphere. Precipitated in surface minerals it produces daughter isotopes, and where this process occurs in a closed system, such as in the formation of calcite crystals, it provides a good measure of the length of time since the formation of the mineral. Several specific decay processes have been used for dating, whose relevance and applicability depends upon their effective time range (deter-mined by the half-life of the decaying isotope) and sample availability. In rock art dating we deal usually with Late Pleistocene and Holocene ages, and in this range only ^{230}Th/^{234}U, ^{231}Pa/^{235}U, ^{226}Ra, ^{231}Pa/^{230}Th and ^{230}Th/^{232}Th may be relevant. The preferred materials for analysis are carbonates (particularly reprecipitated carbonates, such as travertines, speleothems, corals and marl, but also mollusc shells, bone and teeth) but other materials may be suitable. Only one of these methods has ever been applied to rock art, thorium-uranium dating, as noted below.

Finally, a new development in cave art dating is the use of thermoluminescence (TL) analysis to estimate the ages of calcite deposits. Two applications of this experimental method have so far been reported, one in Spain (Arias et al. 2000), the other in Piauí, Brazil. So far the method has not been applied in Australia, but this may only be a question of time. The term TL refers to the release of energy by crystalline solids when heated or exposed to light. Ionising environmental alpha, beta and gamma radiation results in the release of electrons and other charge carriers ('holes') in these materials. Electrons become trapped in defects of their crystal lattice, such as impurities or chemical substitutions. These metastable charge carriers accumulate over time at a known and largely constant rate determined by the dose of the radiation. They can be ejected from their 'traps' by an input of additional energy, causing them to recombine, which releases their excess energy as light, measurable in photons. This energy (TL) is therefore, with some qualifications, a function of the time since the material was last heated (e.g. ceramics or heating stones) or, in the case of rock art, exposed to light (e.g. crystalline mineral grains, such as quartz, but apparently including calcite crystals formed in the recent geological past).

Speleothems in the Mt Gambier rock art sites

In 1980 I located a sequence of calcareous speleothem deposits interstratified with a sequence of petroglyphs in Malangine Cave, in the Mt Gambier karst region of south-eastern South Australia. The art series commences with *mondmilch* finger flutings, followed by deeply carved, apparently non-iconic motifs (Bednarik 1981a, 1984). In the southern part of the cave, the latter generation of rock art precedes the main speleothem 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 fortunately for the purpose of studying the rock art sequence, 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 in the French Dordogne, and in the Australian sites Prung-kart, Nung-kol and Kriton Caves (all in the Mt Gambier region).

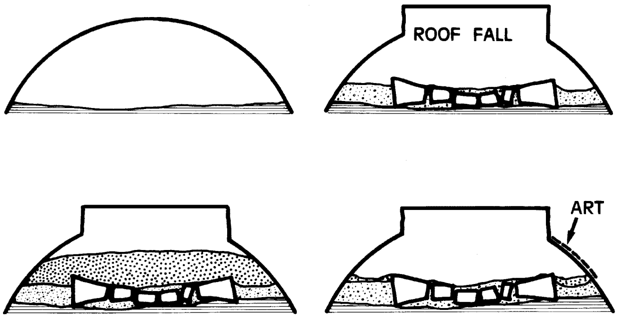

Figure 2. *The sequence of sedimentation, roof fall and rock art in Koongine Cave, South Australia.*

The 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 *mondmilch* panels), which appears to provide a convenient terminus ante quem for the petroglyph production in that cave. The collapsed mass of rock in Koongine Cave is now buried under some one or two metres of sediment (Figure 2), 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 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 (Western Australia).

Finger flutings (Bednarik 1986; *sillons digitales*, Drouot 1976) are a specific type of rock art occurring only in caves, and found so far in two world regions. One is southern France and northern Spain, the other Australia and Papua New Guinea (Bednarik 1984, 1985, 1986, 1990; Ballard 1993). At most of the sites of finger flutings, the former, now often 'fossilised' *mondmilch* (*montmilch*, moomilk, *Bergmilch*, etc.; Bates and Jackson 1987; Fischer 1989) bearing markings is of the speleothem type (i.e. reprecipitated;), but states of preservation differ profoundly between different sites, and often even within an individual site. The finger flutings, usually occurring in sets of three or four sub-parallel finger markings, were made by people who drew the tips of the fingers of a hand over a then soft calcareous cave deposit which has in most cases since become fossilised and calcified. The original deposit is often sufficiently well preserved to still be recognisable; it has usually 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.

The relative chronological framework attempted for the abraded or hammered petroglyphs, the finger markings, calcite deposits, sediments and associated lithic assemblages in Malangine Cave (Figure 3) was the first comprehensive attempt of direct dating of rock art (Bednarik 1981a, 1981b, 1993, 1997). As noted above, about 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 radiocarbon dating of such deposits.

However, there are still qualifications. The most serious concern 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

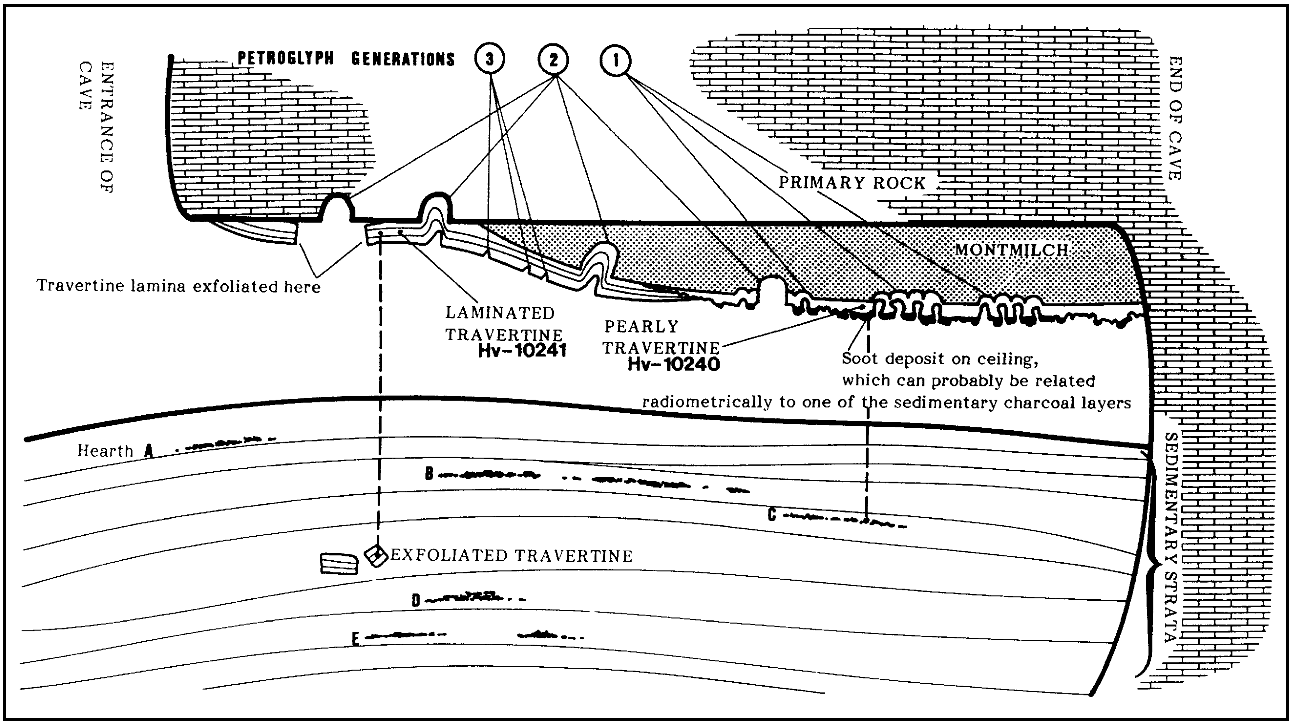

Figure 3. *Schematic depiction of dating framework for Malangine Cave, South Australia.*

deposition, and the rejuvenation it involves. (A possible exception are the well-crystallised stalactites over finger flutings in Kriton Cave, western Victoria.) In fact, we know with certainty that many of the former *mondmilch* 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 appreciably lower during the Pleistocene glacials. This introduces yet another variable, the effect of which is an unknown factor and questions the utility of all Pleistocene radiocarbon dates.

These considerations are only some of those that should temper our sometimes blind reliance on so-called 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 1994, 1996). 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 deposit that separates the two basic art traditions present near that site's entrance (Figure 4). It yielded an adjusted age of 5550 ± 55 years BP (Hv-10241) which might best be described as a highly conservative minimum mean age for the entire lamina. Cutaneous speleothems of this type require substantial time spans for their formation. It may be relevant that 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 are 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. It is, however, squarely contradicted by uranium-thorium analyses of the same deposits (see below).

The second sample processed was from the stratigraphically older, pearly deposit in the deep part of Malangine Cave, which clearly predates the deep petroglyphs and the laminated deposit formed over them but postdates the finger flutings. The radiocarbon age of 4425 ± 75 years BP (Hv-10240) does not contradict the result just cited, it confirms the proposition that rejuve-

Figure 4. *Composite photograph of part of the Malangine Cave ceiling petroglyphs that had been concealed under a thick reprecipitated calcite skin which had subsequently become exfoliated.*

nation can significantly affect the isotopic composition of the speleothem. The highly porous fossil *mondmilch* and the hard excrescence covering it have in all probability remained moist for most of their existence; the subcutaneous stratum has retained a significant content of water to the present time. The absence of any exfoliation suggests that full dehydration may have, in fact, not occurred at all. Greater moistness is apparent even in the recent past, for instance in inscriptions of only eighty years ago. Present hydrological conditions may have been influenced by the effects of pastoral land clearing, which would have led to reduced moisture conservation and lower carbon dioxide production.

In addition to carbon isotope analysis, these two samples from Malangine Cave have also been subjected to uranium series dating in the form of ^{230}Th/^{234}U analysis. A split from sample Hv-10241 yielded a date of 28 000 ± 2000 years BP, and one of sample Hv-10240 produced 4300 ± 500 years. The second value is very similar to the radiocarbon age from the same sample, 4425 ± 75 BP, overlapping most comfortably even at one sigma. The first sample, however, seems to be around five times as old as the radiocarbon age would imply. Unless another explanation can be found, these results would seem to suggest that extensive rejuvenation of the sample has occurred, and possibly also actual contamination (e.g. by organic acids). These results remain inconclusive and are in need of further investigation.

More recently, another site, about 31 km from Malangine Cave, was subjected to a similar study. In Prungkart Cave, finger flutings have been preserved under a laminar speleothem (a calcareous, laminated skin of reprecipitated carbonate in a cave) of 15 to 20 mm thickness (Figure 5). 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 deposit 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. 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 speleothem 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 δ^{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, δ^{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 speleothem 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 1991 reports up to 50.8% porosity by volume 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

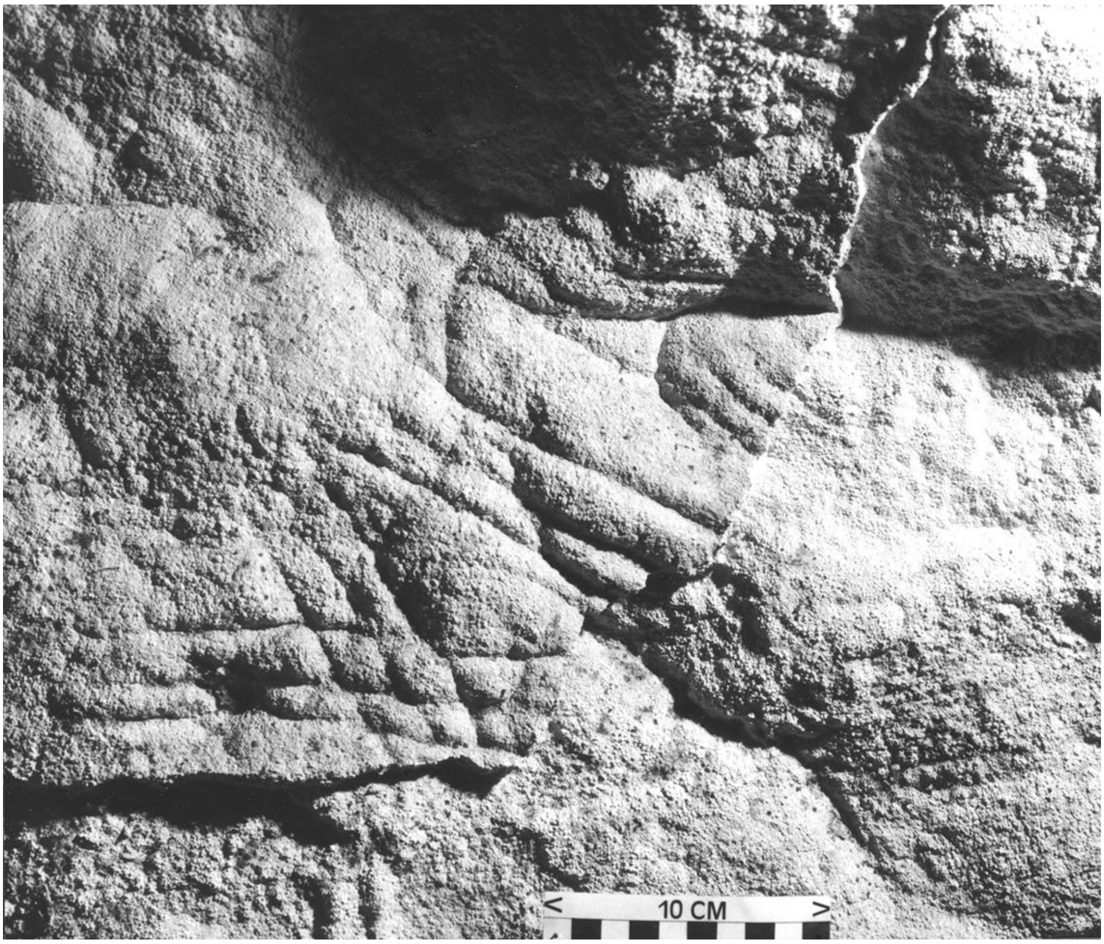

Figure 5. *Finger flutings on fossil (inactive)* mondmilch *in Prung-kart Cave, South Australia.*

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 deposit 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 during deposition 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 reprecipitated calcareous 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 (Hendy 1971). 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 avenues of future research in this complex area. 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 (Morgan 1993) 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.

To clarify the extent of carbon rejuvenation of reprecipitated cave carbonates it is recommended to

- subject the samples from Malangine Cave to TL analysis;
- attempt both TL and uranium-thorium dating of the numerous available samples from Prung-kart Cave;
- conduct radiocarbon, uranium series and thermoluminescence analyses of the stalactitic deposits concealing a set of finger flutings in Kriton Cave.

This strategy would not only clarify the extent of rejuvenation effects on the speleothems, it would also identify the effects of morphological differences of such deposits, and it would provide more secure age estimates for Australian cave petroglyphs than what is presently available.

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