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Paleokarst: cessation and rebirth?

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Abstract

The transformation of active karst into paleokarst by burial, isolation or cessation of process is not necessarily permanent. Paleokarst structures and landforms can be and are exhumed or reactivated, sometimes on numerous occasions. There is not a great deal of similarity between the localities where exhumation and reactivation of paleokarst has been reported. Exhumation and reactivation however have not been reported in many karsts that are similar to those where they have been reported. Exhumation and reactivation appears to be favoured in four situations: - the margins of sedimentary basins overlying grand unconformities, the axes of anticlines, narrow steeply-dipping impounded karsts and where paleokarst fill contains unstable minerals. Six processes are principally responsible for exhumation and reactivation: - per-ascensum speleogenesis, eustatic sea level changes, paragenesis, high density speleogenesis, glaciation, and large-scale meteoric speleogenesis. On some occasions karst landforms, particularly caves or segments of caves, may survive intact and unfilled for geologically significant periods of time. These may be completely isolated from the surface environment, or become reactivated by entrance formation due to breakdown, surface lowering or headward erosion. The intersection and reactivation of ancient open cavities and of exhumed cavities by "modern" caves may be much more common than is currently recognised. If caves have histories as long and as complex as the karsts in which they are developed then many "modern" caves will be composite features composed of interconnected "modern", relict and exhumed cavities excavated at different times by different processes. Unravelling these histories is the new challenge facing cave science. It will require caves to be studied in a much more detailed, thorough and systematic manner and will also require the application of new technologies in surveying, analysis and dating.

Keywords: paleokarst, exhumation, reactivation

Introduction

When does the karst process cease? Does burial under a sedimentary basin or burial and filling with lava put an end to karst forever, or are these just interludes in a long cycle of karst cessation and later rebirth?

There have been an increasing number of reports since the 1960s of karsts in which not only have there been numerous phases of karstification, but also where ancient karst landforms have been exhumed and re-activated. In these cases paleokarst is clearly not the cessation of karst, but only the cessation of one particular phase of karst development.

The following discussion concentrates on the reactivation/exhumation of cavernous paleokarsts related to grand unconformities and on relict karst landforms. *Relict* karst landforms are considered here to be features that have been preserved by isolation from, or cessation of, the processes that formed them. Less emphasis will be given to the more common type of paleokarst; preserved epikarst horizons within carbonate sequences (*intrastratal* paleokarst).

Exhumation is used to describe the process by which filling and covering sediments are removed from a paleokarst feature, particularly a cave or doline, and *reactivation* is used to indicate that karst processes have re-commenced in a feature from which they have been absent for a considerable period of time. While reactivation will generally follow exhumation, it is likely that many paleokarst features (E.g. ancient open cavities and fissures) have never been filled and so can be reactivated without being exhumed.

Young caves may also *intersect* and *expose* parts of ancient open caves. While parts of the ancient cavity system will be completely obliterated by more recent speleogenesis, some exposed forms will be exposed intact, without later modification. The term *young* cave is used to describe any cave that can be entered at the present time. It is important to recognise from the outset that some of these caves may have Palaeozoic origins.

While multiple or polycyclic karstification is common, much paleokarst, particularly intrastratal paleokarst, is never again re-karstified. Some will be subducted, some will never reach the surface and some will be transformed in ways that prevent re-activation. Perhaps the exhumation/reactivation of paleokarst is favoured by particular geotectonic circumstances.

Where does exhumed/reactivated paleokarst occur?

It is not uncommon in the Highlands of southeastern Australia, where my research is based, to find paleokarst deposits and cave forms intersected by, or incorporated into, young caves. However the literature suggests that while multiple karstification is quite common, it is uncommon for young caves to intersect or incorporate paleokarst structures (Osborne, 2000). Cave/paleokarst intersection is reported from a few other localities including:

- The Transdanubian Ranges of Hungary (Korpás, 1998, Korpás et al, 1999; Bolner-Takács, 1999) (A in Fig. 1), The Bihor Mountains, Romania (Ghergari et. al, 1997; Silvestru and Ghergari, 1994)(B in Fig. 1).
- The gypsum maze caves of western Ukraine (Klimchouk and Andrejchouk, in Press) (C in Fig. 1).
- The Black Hills of South Dakota, USA (Bakalowicz et. al, 1987, Palmer and Palmer, 1995, 2000) (A in Fig. 2).
- The Cayman Islands (Jones, 1992; Jones and Hunter, 1994)(B in Fig. 2).

A first step in understanding how paleokarst caves become exhumed, intersected or reactivated might be to consider the geological and geomorphic setting of these localities. The striking thing about the Highlands of southeastern Australia and the five other localities listed above is that they have in very little in common:

- A Palaeozoic fold belt on a passive continental margin. (SE Australia)
- Two Mesozoic European karsts (Hungary and Romania)
- An artesian gypsum karst (Ukraine)
- A Late Palaeozoic carbonate platform sequence. (USA)
- A tropical carbonate island (Cayman Islands),

except that each has undergone some degree of tilting or deformation.

However each is more like other areas where there are no reports of "young" caves being in any way related to ancient ones, E.g.:

- The Appalachian karsts of the USA.
- The Dachstein Limestone karsts of Austria and Slovenia.
- The gypsum karst of Germany (Kempe, 1996)
- Thousands of tropical carbonate islands.

The discussion that follows draws both on the literature and the author's work in southeastern Australia to illustrate situations favouring interactions between paleokarst and "young" caves. Since many examples will be drawn from southeastern Australia, it will assist to provide a brief summary of its tectonic and geomorphic setting.

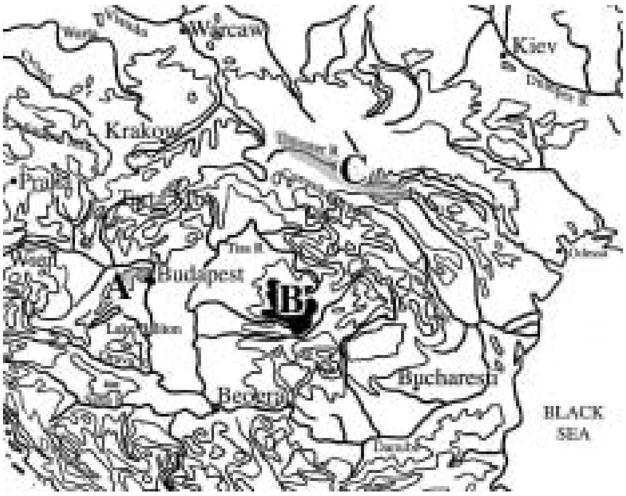

Fig. 1. Central Europe. **A:** The Transdanubian Ranges of Hungary. **B:** The Bihor Mountains, Romania. **C:** The gypsum maze caves of western Ukraine.

Fig. 2. North America. A: Black Hills, South Dakota. B: Cayman Islands, Shading = Kaskaskia Paleokarst after Palmer & Palmer (1995).

The Highlands of southeastern Australia

The Highlands of southeastern Australia (Fig. 3) are developed on deformed Palaeozoic rocks of the Tasman Fold Belt and on relatively undeformed Latest Palaeozoic to Mesozoic cratonic sedimentary basins which unconformably overly the Palaeozoic sequence. Cavernous karsts are developed in limestones ranging in age from Ordovician to early Permian and also in Proterozoic dolostones in Tasmania. There are no gypsum strata within the Palaeozoic or Mesozoic sequences.

Fig. 3. Geological setting of some cavernous karst developed in Palaeozoic and older carbonates in southeastern Australia. AS = Ashford, MC = Moore Creek, KB = Kunderang Brook, YE = Yessabah, CB = Comboyne, TR = Timor, WE = Wellington, BN = Borenore, CL = Cliefden & Walli, A = Abercrombie, J = Jenolan, C = Colong, W = Wombeyan, B = Bungonia, MF = Mount Fairy, WJ = Wee Jasper, CP = Cooleman Plain, WY = Wyanbene, Y = Yarrangobilly, BD = Bendithera, R = Rosebrook, KY = Kybean, I = Indi, LC = Limestone Creek, BU = Buchan, IB = Ida Bay.

The region became cratonised in the Carboniferous and was subjected to significant glaciation during the Late Carboniferous to Early Permian. The present landscape; with a narrow coastal plain, an continent-long erosional escarpment (the Great Escarpment) and low Highlands consisting of incised plateau surfaces, has its origins in the Cretaceous with uplift associated with the opening of the Tasman Sea. Since Australia did not separate from Antarctica until the Eocene, the present landforms, including caves, have Gondwana origins. The idea that caves of the southern continents may have related histories is by no means new and can be found in the work of Lester King (King, 1959).

Paleokarst has been recognised at unconformities within the folded Palaeozoic sequence, where cratonic basins unconformably overly Palaeozoic limestones, and where Tertiary basalts and sediments overlie Palaeozoic limestones.

With the exception of relatively large areas of outcrop in Tasmania, most of Palaeozoic carbonate rocks in southeastern Australia form elongate north-south trending impounded karsts (karst barre), often with steeply dipping strata. Many of the most cavernous karsts are located directly adjacent to unconformable boundaries between the limestone and overlying siliciclastic or volcaniclastic sediments.

Situations favoring exhumation/reactivation

While the six localities discussed in the introduction may have quite different tectonic settings, there are specific local and regional situations that are favourable to paleokarst cavities being exhumed and/or reactivated.

1. The Margins of Sedimentary Basins unconformably overlying soluble rocks

Major unconformities represent significant breaks in the stratigraphic record. The unconformity surface is a buried landscape resulting from an extended period of subaerial exposure. Soluble rocks exposed in these ancient landscapes will develop a suite of surface and underground karst landforms. These landforms will be filled and buried when sedimentation re-commences and the ancient landscape is covered by sedimentary basins. If later in their geological history these sedimentary basins are uplifted and eroded, buried karsts at the basin margins are likely to be re-exposed and subjected to further karstification and possible exhumation/ reactivation (Fig. 4).

This situation occurs both in southeastern Australia and in the northwestern USA. In southeastern Australia the Sydney Basin (Permo-

Carboniferous to Triassic) and the Tasmania Basin (Carboniferous to Permian) both unconformably overlie Early Palaeozoic limestones. The unconformity at the base of the Sydney Basin represents a land surface with a local relief reaching 1 500 m and period of exposure of up to 35 million years. Young caves intersect paleokarst at Bungonia and Jenolan on the southwestern margin of the Sydney Basin and at Ida Bay on the margin of the Tasmania Basin (Fig. 3).

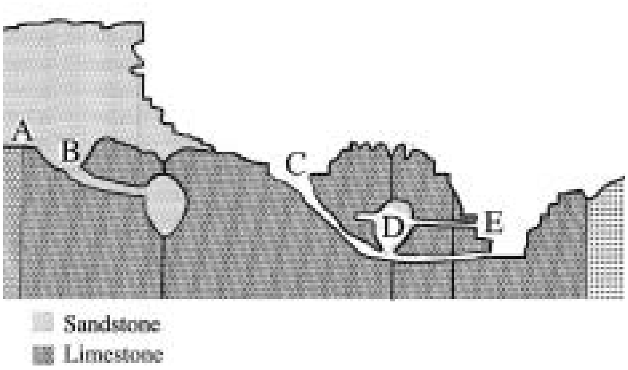

Fig. 4. Paleokarst and unconformities.
A: Unconformity surface. B: Doline in unconformity surface filled with sandstone. C: “Young” doline and cave invading ancient system. D: Ancient cupola, partly exhumed, intersected at base by “modern” cave.
E: Ancient hall from cupola, intersected by valley incision, now forming cave entrance.

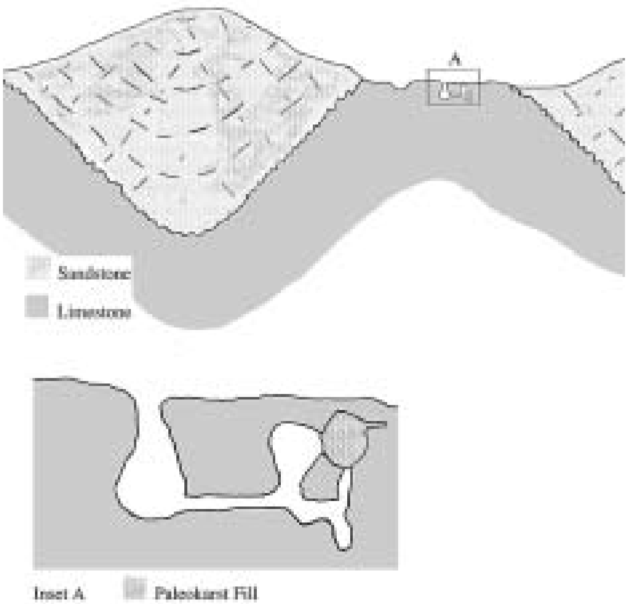

Fig. 5. Paleokarst and Anticlines. Unconformity is between limestone and overlying sandstone. Paleokarst is intersected by modern cave at crest of anticline.

2. The Axes of Anticlines

Where a buried carbonate sequence has been subjected to regional folding with widely-spaced fold axes, the overlying beds will tend to be preserved along the axes of synclines, often forming ranges of hills, and eroded along the axes of anticlines. (Fig.5). Consequently the underlying carbonates will tend to be exposed, and paleokarst reactivated, close to the axes of anticlines. In broad folds close to the anticlinal axis, the orientation of paleokarst structures will be less disturbed than on the limbs. Here vertical paleokarst structures, such as shafts, will approximately retain their original vertical orientation, aiding their reactivation and recognition.

Examples from southeastern Australia include Wellington Caves (Figs 3 and 6) and Wombeyan Caves (Osborne, 1993a).

3. Narrow Steeply-Dipping Impounded Karsts

Subsequent phases of cave development are likely to behave differently in steeply-dipping limestone and horizontally-bedded limestone (Osborne, 1999a). When horizontally-bedded karsts are subjected to further periods of karstification and speleogenesis there is ample opportunity for new caves to form on the same inception horizon, adjacent to the older caves but without intersecting them (see Fig. 15 in Osborne, 1999a).

Fig. 6. Vertical paleokarst shaft of probable Late Devonian age, filled with megabreccia, intersecting thinly bedded limestone bedrock. Cathedral Cave, Wellington Caves, N.S.W., Australia.

Where bedding in thin bodies of limestone becomes steeply inclined following folding, narrow, elongate impounded karsts are produced. In these karsts, laterally adjacent paths may not be available for subsequent phases of speleogenesis. If multiple phases of karstification occur after folding, new caves will most likely form along the same bedding planes as any older paleokarst cavities, possibly at different vertical levels within the bedding planes (Fig. 8). The paleokarst may act as an aquifer and be wholly or partially exhumed, or may act as an aquiclude, forcing new caves to form either above or below it. Consequently it is more likely that new caves will intersect ancient ones in narrow bodies of steeply-dipping limestone than in extensive masses of horizontally-bedded limestone.

4. Where Paleokarst fill contains unstable Minerals

Ancient caves are more likely to be exhumed/reactivated if they are filled with materials that become unstable when exposed to vadose conditions. Osborne (1996) noted the close proximity of some cavernous karsts to ore deposits and described how paleokarst fills containing pyrite were weathering in vadose conditions and being rapidly removed from the caves.

This process will over time result in the complete exhumation of ancient cavities (Fig. 7). One significant feature of these exhumed caves will be their lack of integration with the surrounding modern hydrology. If there are streams in these caves they are likely to be out of scale with the cavities through which they flow.

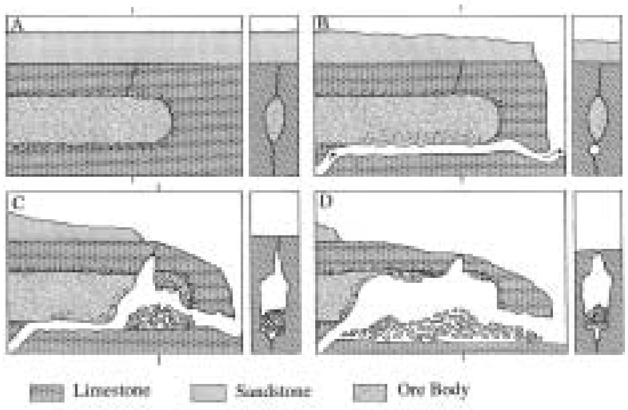

Fig. 7. Cave development by exhumation of ore deposit after Osborne (1996), viewed in cross-section. A: Ore body is emplaced in steeply-dipping limestone, which is unconformably overlain by sandstone cap rock. B: Cave development is deflected by ore body which acts as aquiclude in phreatic conditions. Passage develops under ore body. C: Lowering of water table brings deposit into the vadose zone. Stripping back of overlying cap rock increases exposure of unstable minerals to oxygenated vadose seepage water. Deposit begins to weather and fallen material is removed by modern stream. D: Out-of-scale chamber expands as cap rock is further stripped back. Ore body remnants forming substrate for gypsum and aragonite speleothems.

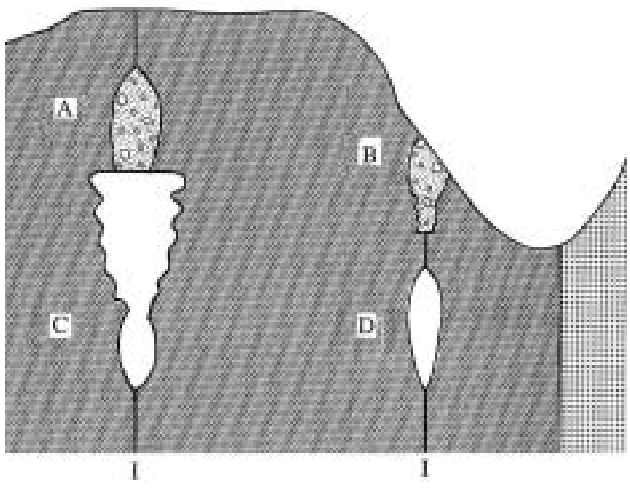

Fig. 8 Intersection of filled cave in steeply dipping limestone as a result of paragenesis after Osborne (1999a). A & B: Filled ancient passages, B is exposed by valley incision. C: Young phreatic passage developed on same inception horizon as A works upward due to paragenesis and intersects A. D: Modern phreatic passage developed on same inception horizon as B.

Processes that may promote exhumation/reactivation

1. Per-Ascensum Speleogenesis

Ford (1995) considered that caves formed by per ascensum processes were more likely to intersect paleokarst than those formed by per descensum processes (descending meteoric water). This is because paleokarst may offer high permeability outflow routes that rising fluids may preferentially follow. Bolner-Takács (1999) described an outstanding example of the intersection of paleokarst by later per ascensum speleogenesis in Beremend Crystal Cave, Hungary. Similarly the gypsum caves of the western Ukraine, formed by artesian processes, frequently intersect paleokarst bodies (Klimchouk and Andrejchouk, 2003).

Eustatic Sea Level Changes

The filling and later exhumation of paleokarst features in the Cayman Islands described by Jones (1992) and Jones and Hunter (1994) are a consequence of eustatic sea level changes. Caves formed during periods of low sea level, were filled during high stands and then intersected and partially exhumed when the sea level fell.

A similar process could occur in areas where sea level changes occur due to both eustatic and volcanic/tectonic processes. Anne Felton is researching raised reef flats on the north shore of Oahu, Hawaii, where young karst features intersect paleokarst, while Grimes (2001) has described possible paleokarst deposits exposed in caves on Christmas Island.

While the formation of paleokarst along the Adriatic coast by Recent marine incursion is well known and documented (Zötl, 1989), there are no reports of caves which were filled during earlier higher level sea stands being exhumed and reactivated.

Both oceanic island and littoral karsts need to be investigated for signs of reactivation/exhumation of paleokarst features that were filled during past high stands and have since been exhumed or reactivated.

3.Paragenesis

Paragenesis can be an important process for exhuming and reactivating ancient caves. This is particularly the case where more recent caves have developed in the limestone mass below the level occupied by filled caves. Osborne (1999a) illustrated the operation of this process in steeply dipping limestones (Fig.8). In this case paragenetic excavation, with dissolution acting upwards above a rising clastic fill, causes a cave formed at a lower level in the limestone to intersect an older feature, located higher in the limestone mass. In the narrow impounded karsts of southeastern Australia there is good evidence for multiple phases of paragenesis, resulting in filling, exhumation and overprinting.

Paragenesis is an important process, as it can not only result in young caves intersecting ancient ones, it can also occur repeatedly and by itself produce a complex of overprinted passages.

4. High density Speleogenesis

Ford (1995) noted that per ascensum caves were more likely to intersect paleokarst than per descensum caves. One possible explanation might be that it is the morphological characteristics of per ascensum caves, rather than their mode of formation, that is responsible for them intersecting paleokarst.

Klimchouk (1996) used the cave index (passage length km/ area of cave field km^2) to distinguish between artesian maze caves (with cave indices of >100) and normal stream caves (with cave indices of <30). Some other caves which intersect paleokarst such as the caves of the Black Hills South Dakota and the Hall and Narrows caves of southeastern Australia (Osborne, 2001a) also have high cave indices.

However, some caves that intersect, or are guided by, paleokarst do not have high cave indices. These include Satorkopuszta Cave in Hungary, the text book example of a point-source hydrothermal cave (Ford and Williams, 1989) and Grill Cave at Bungonia Caves, N.S.W. Australia, a downward-narrowing funnel-shaped cave (Osborne, 2001b). In the case of Grill Cave, paleokarst is intersected in the lowermost, narrow section of the cave, as well as in upper, more expansive sections. In such cases the mode of formation does appear to be crucial.

Irrespective of their mode of formation, however, caves with maze or ramifying morphologies will intersect more of any given limestone mass than a stream cave, considerably increasing the likelihood that they will intersect paleokarst or any other feature preserved in the bedrock.

5. Glaciation

Ford and Williams (1989, pp 482-490) described a number of processes associated with glaciation that can result in exhumation and reactivation. Dissection of karst landscapes by glacial valleys can both intersect and preserve (by isolation) phreatic caves left as high-level relicts in valley sides or close to summits. While infilling with sediment may inhibit later karst processes, coarse clastic fills may act as post-glacial aquifers, resulting in karst features being exhumed. Karsts with glacial pavements may be converted into confined aquifers when covered by till. Meltwater may be focussed into particular ponors, causing rejuvenation of underground drainage, while raising of the local water tables adjacent to glaciers may flood cavities formerly in the vadose zone. Ford and Williams (1989) also described instances where deep injection of meltwaters into karst aquifers, interstratal karst and paleokarst during crustal isostatic depression or rebound (chiefly the latter) has resulted in rejuvenation of buried karsts as old as the Devonian.

6. Large-scale Meteoric Speleogenesis

Most stream caves intersect a relatively small volume of limestone, and as previously discussed are less likely to intersect and reactivate paleokarst than caves with more complex structures. Very large stream caves, or stream cave systems consisting of active and abandoned stream channels at different levels (E.g. the caves of the Demanovska Valley, Slovakia) will intersect a greater volume of limestone than will smaller stream caves and so have an increased chance of intersecting ancient karst structures.

If the earlier caves had a network or ramifying nature, or contained large voids (if the earlier karstification was deep seated, artesian, thermal or otherwise *per-ascensum*) then the chance of a large/complex young stream cave intersecting an ancient cave structure (filled or open) should increase.

Preservation without filling

Ancient caves may be preserved without being partially or completely filled with clastic sediments or precipitates. Some of these will be blind cavities, which have been discovered by excavation or drilling. Others will have gained natural entrances as a result of cliff retreat, surface lowering or other processes that are unrelated to the excavation of the cave.

While it is possible to argue that these relict caves are not truly paleokarst, or that slow deposition of speleothem represents an ongoing vadose process, the caves were principally formed by processes that are no longer active, and fall within a broad definition of paleokarst.

Preservation by Cessation of Process and Isolation

For karst cavities to be preserved in an unfilled, or largely unfilled, condition over a significant period of time:

- the processes which excavated them must have ceased
- and
- they must remain isolated from active surface processes.

The (relict) great gypsum caves of the western Ukraine (Klimchouk, 1996, 2000) and many of the caves of the Buda Hills, Hungary (Dublyansky, 2000) are good examples of preservation by cessation and isolation. In both cases the speleogenetic process has ceased, i.e. the artesian aquifer has drained and thermal waters no longer circulate. Overlying aquicludes, sealed entrances or lack of entrances isolate them from surface processes.

When caves have no natural entrance, as with most in the Buda Hills, their isolation from at least young surface karst processes is clear. These caves must have had exits (outflow points for thermal waters) when they were active. As a consequence of their size, morphology, position in the landscape or becoming sealed the exits have not acted as entrances, allowing meteoric water or sediment to enter.

Isolation by blocked entrances is another matter. As generations of cavers will attest, digs (sometimes) intersect open caves. Cave sedimentologists have also recognised (E.g. Frank, 1975) that cave entrances will open and close over time.

While deltas and cones of entrance facies sediments (fluvial, talus and aeolian) are the most common forms of cave entrance blockage, caves may also become sealed by speleothem, volcaniclastics and lava flows. The effectiveness of such blockages may also mean that open cavities may survive even when a whole karst is buried under sediments.

The important issue is: - are caves that have been isolated by entrance blockages sufficiently unrelated, old and/or isolated from young karst processes to be considered relict and/or paleokarst? This may be a difficult question to answer, but it is an important question to ask and investigate. Caves discovered by digging have the potential to be much older and more significant than may be initially apparent.

Reactivation by vadose invasion

Caves formed by deep phreatic or per ascensum processes may lie dormant in the landscape due to failure of their fluid supply. Much younger vadose shafts or stream passages may intersect these ancient cavities, leading to their reactivation. It is likely that this has occurred at Bungonia Caves, N.S.W, Australia (Osborne, 1993b) and in Derbyshire, England (Ford, 2000).

I have described invading vadose streams in southeastern Australia (Osborne, 1999b, 2001a). These streams are easily misinterpreted as being responsible for excavating the cavities through which they now flow. Sometimes they are distinctly underfit or the passage morphology below the present water level is different in size and morphology to that above. Often a detailed study of cave pattern, wall morphology and speleogens is required to distinguish between a stream which excavated a cave and one which has been captured into a pre-existing system of cavities.

Reactivation by entrance formation

Some caves will never have had an entrance opening to the Earth's surface, while others will have lost their entrance due to blockage. The opening of an entrance will allow some limited interaction with the surface and thus a degree of reactivation Surface lowering, cliff retreat, incision and headward erosion can all form new entrances in caves which previously lacked any surface connection (Osborne, 2001a).

From a human point of the view the importance of these entrances is that they allow us to enter the cave. Because these entrances are natural, unlike when we drill or accidentally excavate into a cave, there is a great temptation to incorporate them into our attempts to understand the origin of the cave. Far too often a non-genetic (intercepted) entrance, particularly one produced by cliff retreat, incision or headward erosion is misinterpreted as a hole through which water flowed into or out of the rock mass.

If we are to recognise ancient caves that have been preserved by isolation and reactivated by subsequent natural entrance formation then detailed attention must be given to the morphology of the entrances and of the deposits in them. In some cases a distinct facies change will occur between internal and surface-derived sediments, marking the opening of the entrance (Fig. 9) (Osborne, 1978).

Exhumation/reactivation with no obvious cause

A number of environments and processes are likely to be favourable or responsible for young caves intersecting, exhuming or reactivating ancient caves. However in many cases where young caves intersect, exhume or reactivate ancient caves it is by no means clear which characteristic of the environment has been favourable to this occurrence, or what process excavated the new cave.

While there are indications that the "Hall and Narrows" caves of Osborne (2001a), many of which intersect paleokarst, may have formed by per ascensum processes, this is by no means certain. Using intersection of paleokarst as an indicator of per ascensum processes may well turn out to be a circular and fallacious argument.

In some southeastern Australian cases, E.g. Timor Cave, an isolated "phreatic" room, situated high in the landscape, which intersects both flowstone and lava-filled paleokarst (Osborne, 1986), the process by which the young cave was excavated, and its relationship with the surrounding landscape, remains unclear. This will be the case with many localities until there is greater understanding and agreement as to which speleogens, patterns of cave development and cave deposits are truly indicative of particular modes of speleogenesis.

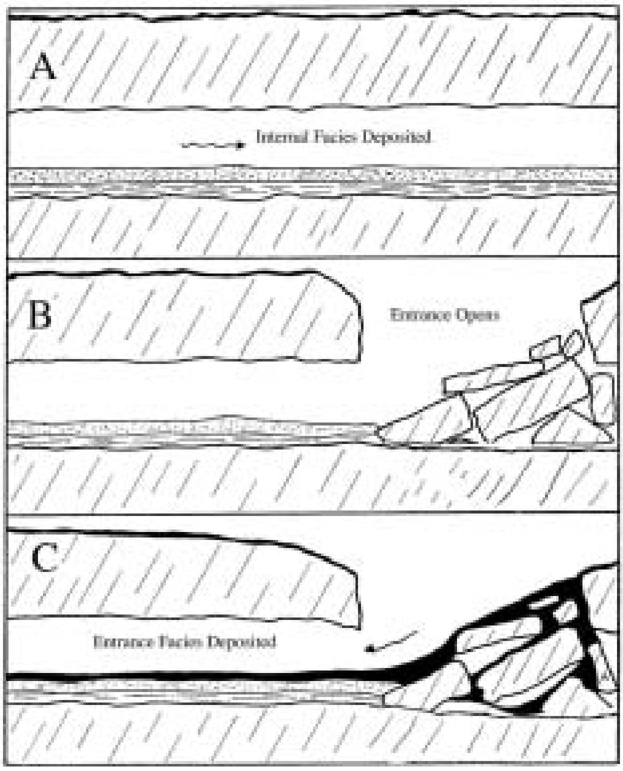

Fig. 9 Cave entrance development after Osborne (1978). A: Closed cave with internal sediments developed. B: Non-genetic entrance opens as a result of breakdown. C: Entrance facies deposited through entrance.

Conclusions

The extensive literature reporting multiple sequences of karstification makes it no longer possible to imagine that burial, marine transgression or isolation will necessarily result in the permanent cessation of karst processes in any mass of soluble rock.

The important questions are now about:

- the extent to which ancient and young karst features interact
- the nature of these interactions
- the extent to which ancient karst features are exhumed

- the processes which result in exhumation
- how to recognise exhumed features
- the extent to which ancient karst features survive as unaltered relicts
- the conditions which lead to survival
- how to recognise relict features
- (particularly when they are incorporated in young systems)

Reports of young caves intersecting ancient caves filled with lithified sediment remain relatively uncommon, and therefore probably relate to specific and less-common speleogenetic processes. These features are often quite striking and criteria exist for their recognition (Osborne, 2000).

Exhumed and relict karst features are not often reported as components of young caves. If more than a few caves have histories as long and as complex as the karsts in which they are developed then many young caves will be composite features composed of interconnected young, relict and exhumed cavities excavated at different times by different processes.

Over the years I have recognised exhumed dolines at Yarrangobilly Caves (Osborne, 1996) and exhumed caves at Jenolan Caves (Osborne, 1993c, 1999b). This was possible only because remnants of the former fills remained adhering to the doline and cave walls and because in some caves exhumation can be observed continuing today. If almost all, or all, of the fill had been removed this would have been almost impossible

Recognition of relict cave forms that have never been filled is even more difficult. Out of scale and out of character voids (E.g. convection cupolas forming the ceilings of stream passages) should arouse suspicion.

A more thorough study and understanding of caves is now required including: -

- Detailed metre by metre examination by skilled observers.
- Mineral surveys; including trace element, fluid inclusion and stable isotope studies to determine paragenetic and speleogenetic environments.
- Very detailed geomorphic (speleomorphic) mapping and imaging.
- Particular emphasis will need to be given to ceiling and wall morphologies, and cross-sections. (reflectorless laser instruments, stereo imaging and graphical databases will assist)
- Absolute dating of cave materials over a greater time range than commonly currently applied. (E.g. K-Ar clay dating, U-Pb carbonate dating)
- More research to identify and understand young active speleogenetic environments. This will require field studies in active speleogenetic environments (often by divers, but also by hydrologists and hydrogeologists) along with physical, mathematical and computer modelling.

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