Cave-Producing Processes in Soft Porous Limestone Regions of Southern Australia

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Abstract

Cave development in the Mount Gambier region, and indeed in soft porous limestones throughout Southern Australia, is very different to that of caves in the massive jointed limestones of Eastern Australia.

The minimal surface relief in Southern Australia is generally associated with caves developed at a single level, often at no great depth below the land surface. Equally obvious is the common single-chamber nature of these caves compared to the greater linear extent of many Eastern caves. Also, it is often clear where surface waters enter a Southern Australian cave, but not where they eventually leave it, in contrast to Eastern Australia where cave effluxes are more common than influxes.

It has long been my view that mixing corrosion has played a far greater role in the development of most caves than has been generally acknowledged, but I am now convinced that this is especially true of the Mt Gambier region in the Lower South East of South Australia. However, the 'solution-tube' features of the Mt Gambier area, which are crucial to the early history of many if not most caves of that region, are not corrosional (solution) but corrasional (abrasion) features. The processes involved in the development of the small Mount Gambier 'solution pipe' caves are of a series with those ultimately responsible for the development of large 'bottle-neck' caves like The Shaft; of large collapse dolines such as Mt Gambier Town Cave (Cave Gardens) and Umpherston Sinkhole; and of the deep 'cenotes' such as Hells Hole.

Key Words: solution pipe, corrasion tube, porous limestone, mixing corrosion, cenote, South Australia, Mount Gambier.

Overview

The 'Solution Pipes' of the Lower South East of South Australia are not solutional in origin at all, but are in fact corrasion features. With apologies to Cliff Ollier (Ollier 1982 p431), we could say that the Solution Pipes of South and Western Australia are a karstographic myth; Corrasion Tubes are however real enough.

These corrasion tubes do show a passing similarity to phreatic cave passages (as the Eastern Highlands show a passing similarity to a mountain range), and they are undeniably tube-like or pipe-like in shape. These facts combined have led to the name 'solution pipe' being applied, and its use has become universal.

Now one can argue that a name is just a name, but our use of language affects our thinking just as much as the converse, and there is a tendency to think that something called a 'solution pipe' is necessarily a solutional feature.

Certain key features give the lie to the notion of a solutional origin or a phreatic setting for what I shall hereafter call corrasion tubes. However, these features do not show up well on cave maps the way we usually draw them, and this (as was the case with Armstrong Osborne's eventual recognition of the true nature of paragenetic loops) has hindered the recognition of their real nature.

Caves and Cave Maps

The features of the way we map caves that have contributed to this lack of understanding are:

- an emphasis on the use of a *projected* plan view for the horizontal plane;
- a single *sectional* view (cross- or developed long-section) in the vertical;
- the near universal absence of even a single horizontal section of appropriate features; and
- the use of multiple sections of passages only to show varying cross-sections, and never to show the *unvarying* nature of a passage.

As illustrated in Figure 1 below, the corrasion tube (if not its remarkable nature) is visible in the long section, but almost disappears in the plan view.

Corrasion Tubes – dominant features

The dominant features which argue against a solutional origin are not all displayed to the same remarkable degree by all examples of corrasion tubes, but are displayed across such a large number of examples as to require an explanation consistent with a theory of the origin of the corrasion tubes.

Very many corrasion tubes display the following properties: incredible constancy of cross-section; remarkable straightness and near-perfect verticality

Though less remarkable than the above properties, the corrasion tubes also display a range of characteristic shapes. The most common shape is circular to sub-circular or oval. Amongst the rest, a figure-8 shape is very common. Whether this represents a true different shape,

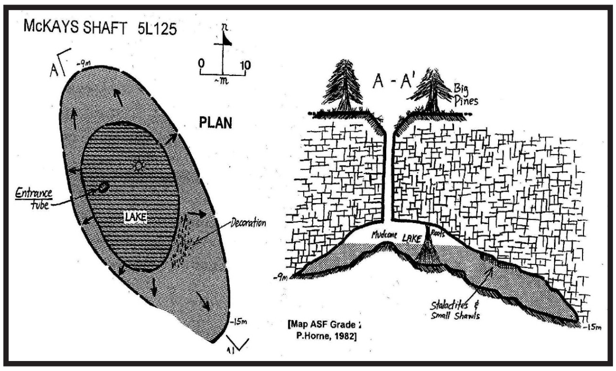

Figure 1: *Map of McKays Shaft (5L125). (Horne, 1993)*

or the overlapping of two sub-circular tubes is a question we shall return to later. For now we shall consider the three features noted above.

Constancy of cross-section

Some idea of the consistent size of the corrasion tubes can be gained from looking at the long sections of the caves, but this gives little idea of either the actual cross-sectional shape or of its incredible constancy.

Typically of a 'diameter' of 0.3 -1.0 m and a (vertical) length of 5 - 15 m, the corrasion tubes usually have walls that are not totally smooth, but display a rippled surface 'texture' at a scale of 1 - 2 cm. Apart from a metre or so at the top of the tube, which may be somewhat widened, and a slight narrowing often seen in the bottom half metre or less of the tube, the size and shape of the tube is typically very constant along its length.

Many if not most of the corrasion tubes display a cross section over most of their length that is constant in both size and shape to within the scale of the surface texturing of the walls – that is, to within a 1 or 2 centimetres.

This is remarkable, and is certainly not typical of cave passages which are of unargued phreatic or solutional origin. Phreatic passages may show a rough consistency of cross-sectional area along parts of their length, and even sometimes a similarity of shape for some distance (e.g. 'tear-drop' joint-guided passages, or oval passages aligned with the bedding), but in my experience phreatic cave passages never show the absolute constancy of size and shape that is so common as to be characteristic of the corrasion tubes.

Remarkable straightness

Although 'linear' features are not uncommon in nature generally, such features when examined more closely usually prove to be distinctly sub-linear. Corrasion tubes are very often truly linear to the degree that can be determined by eye, and to within the 1 or 2 cm of surface texture of their walls. Where they are not linear over their entire length, they often show 2 linear segments with a simple offset part way along. This offset is typically of the order of the tube's diameter or less, so that it is still possible to look through the entire length of the tube.

True phreatic passages *never* show this degree of linearity. Even where they show a fairly regular cross-section it is rarely possible to see more than a few metres along them due to their varying direction – i.e., their lack of straightness. Joint-and-bedding-controlled passages may occasionally display the kind of straightness that is typical of corrasion tubes, but these passages are not solutional features.

The only solutional features which typically display this degree of straightness are those associated with a water surface (e.g. river incuts), and for obvious reasons these are always horizontal or, where rock movement has occurred since their development, sub-horizontal features. They are *never* vertical!

So corrasion tubes appear to be unique amongst cave features in being truly straight and vertical, and are certainly unlike any known solutional cave features in this respect.

Near-perfect verticality

I have not had the opportunity to properly measure the properties of a range of corrasion tubes (cross-section, straightness and verticality), but I have dropped ropes down a fair number of them and many or most appear to be vertical to within a few degrees or less. Although many natural features may typically be sub-vertical (e.g. trees, cliffs, joint planes in sedimentary rocks), few if any are typically truly vertical as is the case with corrasion tubes.

Indeed, corrasion tubes show such a dominating verticality that it may well be true that any deviation from verticality must be due to rock movements since the tube's formation. If this is so, then a survey of the precise angles of a range of corrasion tubes (combined with dating of the material found below them), may well prove to be a method for determining the history of small scale land movements in a region.

Although a generalisation, it is probably true that all natural features which are truly horizontal or are truly vertical have been guided or controlled by gravity. Corrasional processes may be driven and therefore guided by gravity; solutional processes, dominated by random ion transfer processes in a fluid, are not gravity controlled (except insofar as the fluid surface and processes associated with it, such as river incuts, may be horizontal). The evidence against a solutional origin for these tubes, and in favour of a corrasional process, seems to be mounting.

One further important feature of corrasion tubes is that they occur commonly in recent, poorly consolidated limestones such as Tertiary or Quaternary shelly marine limestones or coastal aeolian calcarenites, but never in hard massive Palaeozoic limestones such as are typical of the east coast of Australia. These recent unconsolidated limestones are characterised by their softness, and by high porosities and permeabilities compared to other limestones.

We shall now examine how the development of the corrasion tubes may have been affected or guided by these characteristics of the limestone in which they form.

Features of modern, unconsolidated limestones

The features of modern, poorly consolidated limestones which are relevant to the present discussion are:

- they can be *incredibly* soft;
- they have very high porosity and permeability;
- caprocks can form very quickly; and
- caprocks may be remarkably similar to those on more massive, consolidated limestones.

These features, and the effects they have had on the development and nature of the caves found in the Lower South East of South Australia, are discussed below.

Softness of the rock

'Limestone' is an over-loaded word! It is used to refer to a range of rocks that, apart from broad chemical composition, show probably less similarity to each other than do chalk and cheese. East coast cavers think of limestone as this stuff that, depending how hard you hit it, will break either your hammer or your wrist. Climbing holds are strong and reliable, and while their contents may be delicate the caves themselves are extremely rugged, and the concept of 'sacrificial caves' that can be damaged but not destroyed by Scout, school and army groups at least makes some sense.

The contrast with Western Australian aeolian calcarenites, and the caves developed therein, could hardly be greater. Here I once wondered about the integrity of the rock comprising the ceiling under which I was passing. I tested it with my finger tips and three fingers disappeared into the 'rock' up to the second knuckle! I did not hang about to conduct more tests. Climbing on such rock inside a cave can be more a matter of luck than skill.

Limestone such as is found at Jenolan Caves is so hard as to be virtually immune to mechanical attack except under the most extreme of energetic conditions (e.g. major flood flows with contained abrasive sediments and rocks), and it can be fairly said that most cave features, even if structurally guided, are solutional in form. Even undeniably vadose sections of caves are often modified phreatic passages after lowering of the local water level in that section of the cave.

The converse is true of the very soft South and West Australian coastal limestones, which are typically so soft that mechanical breakdown will rapidly erase any traces of solutional processes which may have operated in their past. It is often only underwater (where they are still operating), or very near the ground surface (where they are preserved in the harder surface caprock) that solutional processes are evident.

Porosity and Permeability

An important characteristic of the unconsolidated marine limestones and aeolian calcarenites is the existence within them of extensive, and extensively connected, pore spaces. The percentage of the rock which is pore space – and which may potentially be occupied by water – is its porosity. The connectedness of these pore spaces determines how readily water may pass through the rock – as through a sponge – and is measured as the rock's permeability.

The high porosity and permeability which are typical of these limestones means that water can move within the rock body (whether as a ground water mass or as meteoric water percolating down through the rock), without the prior development of conduit-type passages within the limestone. The porous and permeable nature of the rock affects the way that water flows through the rock, and ultimately the style and nature of the caves that develop within it.

That ground water movements around Mt Gambier and similar locations are primarily by percolation through the porous limestone, and not by conduit flow as in underground rivers, is supported by two kinds of evidence;

1. Studies of trace elements and pollution movement within the region such as that undertaken by J. D. Waterhouse of the S.A. Department of Mines (Waterhouse, 1984)

2. The complete absence of any long conduit-style caves in the region discovered by either wet or dry cavers.

Thus the typical cave of the Lower South East comprises a single chamber, or a number of highly interconnected chambers within a small geographical area, connected to the surface by one or more sub-vertical entrances. The multi-chamber caves (Snake Hill for example) are generally sub-circular in overall plan (as opposed to being elongated or linear in overall shape), and may represent a number of single-chamber-single-entrance caves which have overlapped or intersected each other.

Exceptions to this pattern exist – most obviously Tank Cave with its several kilometres of grid-network passages and absence of large chambers, and those linear caves such as Morgans Cave which appear to be developed for short distances along near-surface joint structures – and these require a different theory of their origin and development. However, the pattern of caves with a single sub-circular to oval chamber, and one or a few vertical entrances, clearly exists and requires explanation in terms of the regional landscape, climate and rock types.

Development of caprocks

It is my experience that all limestone caprocks are remarkably similar, compared to the wide range of different limestones on which they form. Indeed, the caprock is typically so hard and impermeable as to be similar to the ancient massive east coast limestones which are too impermeable to ever form a distinct caprock layer at all.

The caprock thus often conceals the true softness of the underlying limestone.

It is also noticed, from an examination of road cuttings in the Mount Gambier area, that the caprock develops to a significant depth on any upwards-facing surface in a matter of a few decades. (Overhanging surfaces not directly subject to rainfall and runoff remain soft, with no caprock, on these timescales).

As near as I have been able to determine this caprock constitutes a continuous surface covering, largely impermeable to water, irrespective of at least a thin covering of soil and vegetation. Thus, after development of the caprock, any rainfall tends to run across the surface rather than penetrating the rock and descending to the water table over a large area.

However, the caprock is regularly perforated by half-meter scale holes which allow the rainfall to penetrate the surface, so that at a broad scale there is the lack of surface drainage that is typical of limestone terrains.

Some of these perforations are in the form of corrasion tubes penetrating to caves beneath. It is my contention that the remainder are 'failed' corrasion tubes, and that all are due to the existence of a tree early in the landscape history – i.e. before the caprock was able to form. The 'failed' corrasion tubes are those which have not developed a cave beneath them into which material may fall; the tube has therefore been filled in by sediments descending from the surface.

How Corrasion Tubes get Started

Figure 2 (below) shows a number of similar features appearing in the wall of a quarry near Penola in South Australia. They are in my opinion 'failed' corrasion tubes, and evidence from quarry walls would suggest that such 'failed' tubes are much more common than the 'suc-

***Figure 2:** 'Failed tubes' in wall of quarry near Penola, SA. (Photo by author)*

cessful' tubes with a cave existing beneath them.

I believe that these features represent the root systems of trees which existed early in the landscape history before the development of an impermeable - and essentially impenetrable - caprock. The existence of similar features in non-carbonate landscapes, as in Figure 3 below, argues that these are not solutional features, but are formed by the mechanical action of tree roots pushing the still-soft sediments aside.

The evidence supporting the contention that the corrasion tubes are due to trees established early in the history of the landscape falls into two categories: the evidence that they are due to or associated with trees; and the evidence that said trees must have existed very early in the landscape history. These two are discussed separately below.

Evidence for a tree-related origin for the corrasion tubes

The evidence for a tree-related origin for the corrasion tubes is circumstantial and not totally conclusive, but is nevertheless quite strong. It comprises:

• the number and distribution in the land-scape of the tubes;

• their size and shape;

• the necessary association of a tree with a hole in the ground for its roots; and

• the apparent lack of any other reasonable explanation.

***Figure 3:** Erosion gully and 'failed tube' feature in siliceous sands, near Lake Mungo, NSW. Photo: Wayne Cook.*

The number of corrasion tubes, and their spatial distribution in the landscape where the limestone is reasonably exposed, is not dissimilar to the number and distribution of trees in those areas which seem representative of the natural landscape; and is similar to the apparent distribution of trees in such records as we have of the landscape prior to occupation and clearing by European settlers. An important source of information regarding the latter distribution is in the paintings of George French Angas, dating from the mid to late 1840s, many of which were examined by this author when on display at the Riddoch Art Gallery in Mount Gambier. Angas's paintings also provide interesting evidence regarding pre-settlement water table levels, suggesting that they may not have been as much affected as is generally believed by past and current European land use practices. Of course neither the precise number of existing tubes nor the precise early distribution of trees is known, but the numbers and distribution appear sufficiently similar to not discount the hypothesis of a causal link between the two.

The typical size range of the corrasion tubes, being between 300mm and 1 m, is certainly consistent with the normal diameters of the trees presently found in the landscape.

The shape of the corrasion tubes is normally circular or sub-circular, and this is certainly also true of the trees in the landscape. More compelling, however, is the coincidence between the second most common shape of the tubes and the second most common shape of tree trunks, being that of two overlapping circles, or a 'figure-8' shape. Without having done an actual count, it would appear that a few percent of corrasion tubes and of trees adopt this shape. It seems highly significant that *no other shape is common for either trees or corrasion tubes*.

We know that where a tree exists, a root system exists to support it, and that said root system requires a void in the ground, be it of soil or rock, to contain it. That void or hole, at its top, would be about the size and shape of a typical corrasion tube.

Finally, while a causal association between tree roots and corrasion tubes seems on the face of it to be reasonable, and supported by the evidence quoted above, no other explanation has to my knowledge emerged which is consistent with the all the observed features. Certainly the idea of a solutional origin does not appear to fit the known facts.

Evidence for an origin early in the landscape history

Examination of road cuttings has convinced me that a caprock of significant depth (10 cm or more) forms very quickly on exposed limestone of the porosity and permeability which is typical of the Lower South East. (Whether it forms at a similar rate when under a thin soil cover is still an open question, but there seems no reason to believe that such a soil cover would significantly retard its development; indeed, it may even enhance it by acidifying the water passing through, and hence promoting the dissolution and redeposition of carbonate which appears to create the caprock).

Once the caprock has formed, it is very hard and brittle. It is therefore unlikely that the roots of a tree would be able to penetrate it, and nearly certain that if they did so, then there would be evident cracking of the rock around the resultant hole or tube. Having viewed many tens or hundreds of such tubes, from both above ground and from within the caves beneath them, I have NEVER seen any cracking of the rock around them, nor any secondary evidence such as pieces of the limestone beneath the hole. Where the hole is occupied by an existing set of tree roots, the roots conform to the shape of the hole with no indication of their having modified that shape. Thus in typical 'corrasion tube caves', there are often roots penetrating the ceiling of the cave in a circular or sub-circular form (this is typical of dive sites such as The Pines and others, as well as many of the dry caves in the pine forests around Mt Burr and elsewhere). Where there are slot-like holes in cave ceilings, as is the case in apparent near-surface joint controlled caves such as Morgan's Cave, the tree roots emerge in a fan form along the linear crack. In neither case is there any evidence that the current root system has in any way modified the shape or size of the hole that they occupy.

The above all suggests that the tubes have formed early in the landscape history, while the rock even at the land surface is still soft and 'crumbly', rather than hard and brittle. This would place the formation of the initial holes through the surface of the rock in the first few decades of the existence or exposure of that land surface, and thus within the first generation of tree coverage of the landscape. Later density of tree coverage – except where a significant later soil cover has developed – may in fact be limited to that of the original coverage by the need for new trees to re-occupy earlier root holes.

The Role of Mixing Corrosion

Mixing corrosion occurs when two waters of different chemistry (usually, but not necessarily, different CO_2 contents) are mixed. Even if both water sources are individually saturated with respect to calcite, the product of their mixing will be under-saturated and hence will again be aggressive (i.e. able to dissolve more calcium carbonate). This process, responsible for much cave development, is explained in Figure 4 below.

I will argue that ground water moving by percolation through porous rock such as that found in the Lower South East rapidly becomes saturated (and loses its aggressiveness to limestone), and so cannot be directly responsible for the formation of caves far from its point of origin. Cave development requires that some process renew the aggressiveness of the water; and that process usually, and in this case, is mixing corrosion. (Of interest here is Alexander Klimchouk's 'Hypogene Speleogenesis' which clearly relates the development of deep phreatic or hypogene caves to the 'leakage' of water between different depth aquifers, or between the surface and deep aquifers – i.e. to at least the possibility of mixing corrosion.)

The actual chemistry of the dissolution of limestone in water (with carbon dioxide present) is surprisingly complex, as Figure 5 below suggests (Dreybrodt, 1988) However the following generalisations are reasonable:

• in an open system (i.e. open to an 'air' surface from which the water can continue to absorb CO_2), the rate-limiting factor for the complete process is the rate at which CO_2 is dissolved into the water, and

• that in a closed system (no access to an 'air' interface to replenish dissolved CO_2), the ovarall rate-limiting factor is the diffusion of ions across a laminar flow interface near the limestone walls.

Seepage flow through porous rock is essentially a closed system. However, even though the actual flow between grains is laminar, the mixing of packets of water at the boundaries of grains makes ions diffuse at the larger scale as though in a turbulent flow. Ion diffusion is therefore rapid, and the process comes to equilibrium (and the water becomes saturated) very quickly – within minutes if not within seconds.

Given that the 'residency' time of ground water in its aquifer is usually estimated in terms of centuries or

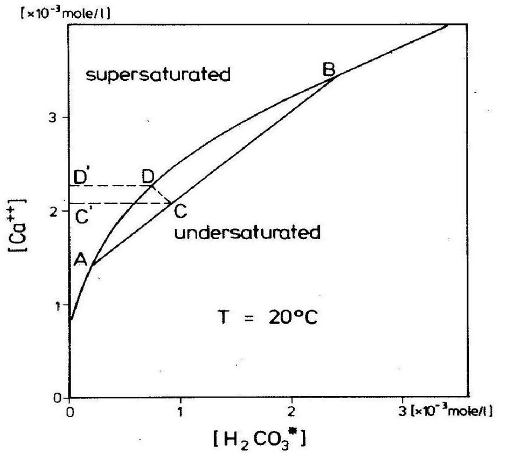

Fig. 2.16. The equilibrium curve divides the $[H_2CO_3^*] - [Ca^{2+}]$ diagram into two parts. *Above*: The curve solutions are super-saturated; *below*: undersaturation exists. Mixing of two saturated solutions (*A*) and (*B*) leads to an undersaturated solution (*C*). The additional amount of Ca^{2+}, which can be dissolved after mixing is given by $\overline{C'D'}$

***Figure 4:** Mixing corrosion with saturated waters. (Dreybrodt 1988 p29.)*

millennia, the statement above that ‘ground water …. cannot be directly responsible for the formation of caves far from its point of origin’ would appear to be justified.

It is worth noting that while mixing high CO_2 saturated water from the surface with different but also saturated ground water will lead to dissolution and the enlargement of any cave, the descent of high CO_2 saturated water of itself is more likely to lead to the deposition of calcite within a cave (due to off-gassing of CO_2 into the cave atmosphere). Thus it is well decorated caves, rather than large caves, which may be indicative of a past vegetative cover, and high CO_2 content in infiltrating water.

Other Modifiers of Aggressiveness

Mixing corrosion is not the only factor which can change the aggressiveness of otherwise saturated water. Some other factors are considered below.

• Rising CO_2 – usually of volcanic origin – can first increase and later (with reducing pressure) decrease the aggressiveness of ground waters through which it passes. This may have played a role in some of the deeper cave developments in the Lower South East, though not in the development of corrasion tubes and their associated caves.

• Sulphate chemistry can have very significant effects on the aggressiveness of ground water or meteoric waters entering a cave. While this has likely played a role in the Nullarbor, there is no evidence of it having done so in the Lower South East.

• Reduction of the temperature of water generally increases (or renews) its aggressiveness. This is unlikely to be a significant factor.

• Other dissolved ion species (Magnesium, Nitrates, etc) can have complex effects on the aggressiveness of water; however such effects are probably of small consequence except in highly extreme water chemistries.

Where phreatic waters are very still, gravitational stratification of the water body may render the upper part of it aggressive – producing ‘un-mixing corrosion’. (I have previously postulated that convection cells based on this process are responsible for the development of the highly conical, half metre scale ceiling cavities found in some of the caves at Naracoorte).

While rising CO_2 and sulphate chemistry can be significant factors in cave development where they occur, mixing corrosion between waters with different CO_2 contents is the generally dominant mechanism producing renewed aggressiveness of water and the development of large cave passages and chambers.

Early Stage Development of a Corrasion Tube Cave

If, as claimed above, the development of an incipient corrasion tube is associated with a tree occupying the landscape prior to the development of a caprock layer, the next question is how and why some of these develop to the next stage; an actual corrasion tube with a cave beneath

The full development of the tube and the development of the underlying cave are intimately linked. The process depends on the tree roots actually reaching the water table, allowing access to the ground water by meteoric water (rain water) entering the hole created by the tree roots (either while the tree still occupies the hole or after the demise of the tree). Mixing corrosion can then occur and a cavity – i.e. a small cave – can develop below the root cavity.

Following the final demise of the tree (or series of trees) occupying the hole, and also following the development of the caprock layer, water is able to freely enter the hole and fall to the (small) cavity below. Two things now occur:

1. While the shape and size of the top of the hole are protected and preserved by the hard caprock layer, the falling water is able to mechanically abrade (i.e. corrade) the still very soft limestone below the surface. Since the water falls under the influence of gravity, the tube ends up with absolutely vertical walls and hence has a regular cross section (shape and size) for its whole length.

2. Mixing corrosion continues to occur in and around the underlying cavity as the rain water enters and mixes with the ground water, thus enlarging the cavity into a full-blown (albeit single chambered) cave. This allows room for the material falling down the tube from the surface, as well as the material abraded from its walls, to be accommodated without blocking the tube.

Hence both the corrasion tube and its underlying cave are formed in concert by the one process. This early stage of the corrasion tube and cave development is illustrated by the example of 5L184 shown in Figure 6.

Of course in many cases sediments will enter the hole at a rate which exceeds the ability of corrosion to either

Systems CO_2–H_2O and $CaCO_3$–CO_2–H_2O

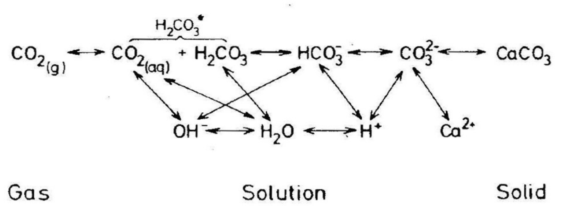

Fig. 4.1. Chemical reactions during dissolution of $CaCO_3$ according to the system CO_2–H_2O (Usdowski 1982)

The generally used reaction equation for dissolution of limestone:

$$CaCO_3 + H_2O + CO_2 \rightarrow Ca^{2+} + 2\,HCO_3^-$$

is such an overall reaction, since it comprises three reactions not appearing explicitly in this equation.

***Figure 5:** Chemistry of dissolution of Calcium Carbonate in a ‘simple’ $CaCO_3$ – H_2O – CO_2 system. (Dreybrodt 1988 p62.)*

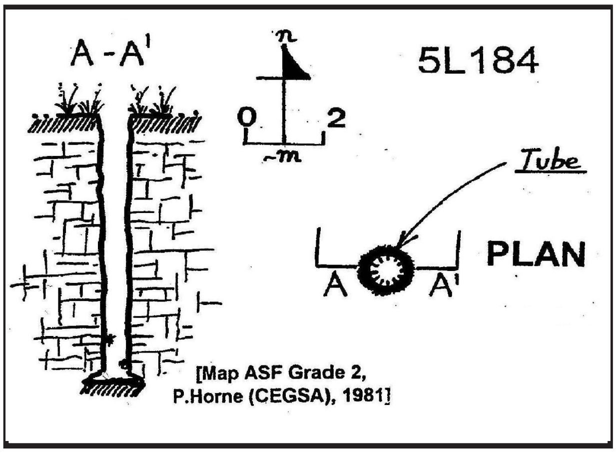

***Figure 6:** Map of karst feature 5L184. (Horne, 1993).*

remove or, alternatively, to create sufficient space for by the enlargement of the cavity. In this case the tube will either fail to complete or will be blocked by the infalling sediments. This is most likely to happen early in the development process; or where there is a large quantity of non-soluble (probably siliceous) sediments; or both. If the tube blocks after the development of a cavity or cave below, then the cavity is likely to remain, but not to further enlarge due to the absence of entering meteoric water to drive the mixing corrosion process. 'Incipient' or 'failed' corrasion tubes (as seen in the quarry wall, Fig. 2, above) appear to be more common than 'successful' corrasion tubes with underlying caves.

Where the tube reaches the underlying water table, and does not become blocked by infalling siliceous sediments early in its history, the enlargement of the underlying cavity or cave is enhanced by the porous and permeable nature of the limestone. This allows the mixed water to actually enter the rock around the existing cavity; thus the cave forming process can proceed much more rapidly than it would in a massive limestone, and dissolution of the cave may stay ahead of the filling of the hole by infalling sediments.

Note that where several trees are close to each other, only one of them need 'succeed' as a cave-forming corrasion tube; it creates the cavity within which material from the other 'incipient' tubes may be accommodated, thus helping the other holes to eventually become 'proper' corrasion tubes. This may explain the number of caves which have (or obviously have previously had) multiple corrasion tube entrances.

The Collapse or 'Cenote Forming' Stage

As the cave or chamber below the corrasion tube gets larger, breakdown of the walls and ceiling will start to occur. This process may accelerate if the water table falls, or the ceiling recedes, sufficiently to remove any support of the rock due to buoyancy.

Regardless of the shape of the resultant chamber, it is a mistake to think in terms of 'dome chambers' or, worse yet, 'collapse domes'. In soft, weak, horizontally bedded limestone such as is found in the Lower South East of South Australia, the relevant structural paradigm is not that of a dome, but of cantilevered beams. Particularly if the bonds between the beds or layers of limestone are weak, each layer will act as a cantilevered beam and is subject to maximum stress - and therefore most likely to break off – where it overhangs the layer beneath. The end result is typically sub-vertical walls, and a flattish or stepped horizontal ceiling which continues to retreat.

If the water table remains high and mixing corrosion continues to occur, then the fallen material will tend to be removed; the 'floor' height will tend to remain stable as the ceiling recedes; and the chamber will get larger. If however the water table falls below the effective floor level (or if the corrasion tube entrance becomes blocked), then the removal of material by mixing corrosion will effectively cease; and since the fallen material takes up more space than it did in situ, the cave will actually get smaller as it rises. Eventually the cave may fill with its own breakdown material, providing support for the ceiling, and halting the breakdown process.

The retreat of the ceiling due to breakdown may also become stalled at a particularly competent layer of rock – such as the caprock – resulting in a large cave still with a (probably shortened) corrasion tube entrance. The Shaft is an example of this type of cave. Alternatively the ceiling may retreat all the way to the surface resulting in a 'cenote' such as Hells Hole, or (depending on the current water table level) a dry cylindrical doline such as Umpherston Sinkhole.

The Complete Development Sequence Summarised

The table below summarises, and Figures 7 to 11 illustrate, the complete development sequence discussed in this paper, from original tree roots to final (wet or dry) cylindrical doline. As discussed above, the process may halt at virtually any of these stages, and for a variety of reasons. In particular, significant amounts of siliceous sediments may enter the cave, blocking either the entrance tube or access to the water table, and preventing further enlargement by mixing corrosion. The cave or doline may then become partly or completely filled by silicates.

Many of the caves of the Lower South East of South Australia appear to represent one or another of the stages in this sequence.

Corrasion Tube Caves – stages of the postulated development sequence:

1. Trees penetrate the still-soft limestone with roots reaching to the water table (Fig. 7).

2. Mixing Corrosion at or near the water table produces a cavity within the rock (Fig. 8).

3. Corrasion Tubes form by water abrading the sides of the root hole, with excess material being accommodated in the existing cavity (Fig. 8).

4. Enlargement of the cavity occurs by mixing corrosion involving meteoric water – possibly enriched in organic CO_2 – entering via the corrasion tube and mixing with the ground water (Fig. 9).

5. Breakdown of the cantilevered beam structure of the chamber causes the walls to become more vertical and the ceiling to retreat upwards (Fig. 10).

6. Continued mixing corrosion of the fallen material at or near the water table allows the chamber to become larger (rather than choking and becoming smaller) as the ceiling rises through the landscape (Fig. 10).

7. Eventually the ceiling may break through to the surface producing either a dry cylindrical doline, or a 'cenote' (a wet cylindrical doline) (Fig. 11).

Note that the use of the term 'cenote' with reference to the open, water-filled caves of the Lower South East may, like 'solution pipe', be misleading and should perhaps be re-considered. There is little if any evidence to suggest that caves such as Hells Hole have formed in the same way as the 'classical' cenotes of the Yucatan. They do not resemble them in shape or form, and importantly are not inter-connected by conduits below the water table. However, they are clearly related to the dry cylindrical dolines of the Lower South East such as Umpherston Sinkhole, Town Cave etc, and should perhaps simply be called wet cylindrical dolines.

Corrasion Tube Caves - some final thoughts

We have established that the intersection of a corrasion tube and its associated underlying cave is not accidental; the two features are geomorphically related. We also know that corrasion tubes can close off due to accumulation of sediment cones in the cave below, but may also re-open due to erosion of those sediment cones.

Such is the nature of the landscape in the Lower South East – flat and generally quite clear – that we can be fairly confident that the overwhelming majority of the open corrasion tubes leading into caves are known. Even within the pine plantations (where obviously the tree cover is denser), most such cave entrances have been found and often fenced off to prevent damage to equipment or, one hopes, to the cave.

Now, while blocked corrasion tubes which intersect a cave may be difficult to locate and identify from above ground, they are generally quite obvious from within the cave. It is a simple (if time-consuming) matter to enter these caves and count the number of open, and the number of blocked corrasion tubes intersecting each cave.

Given this information – the statistical distribution of the number of blocked and the number of open corrasion tubes per cave for those caves where the latter number is greater than zero – it should be possible to make an estimate of the distribution of the number of blocked tubes per cave for those caves where the number of open corrasion tube entrances is zero.

Furthermore, using bulk single grain luminescence dating of the silicates from the sediment cones beneath both blocked and open corrasion tubes, it may be possible to estimate the rate at which the blocking and re-opening cycle of the entrances typically operates, and therefore the percentage of the time that a corrasion tube entrance typically remains open. (The Photon Counting Imaging System, a new variant of luminescence dating technology currently under development by the author, should make such a large single-grain dating project feasible at a future date.)

Finally, by combining the above two estimates, it may be possible to deduce a figure for the total number of caves in the Lower South East of South Australia, with one or more blocked corrasion tubes and exactly zero open corrasion tube entrances. It would then be possible to provide something other than a facetious answer to the apocryphal tourist question: 'How many undiscovered caves are there?'

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References

Dreybrodt, Wolfgang 1988. *Processes in Karst Systems: Physics, Chemistry and Geology.* Springer-Verlag

Horne, Peter 1993. *Lower South East Cave Reference Book*. Peter Horne and the Cave Exploration Group of South Australia (Inc).

Klimchouk, A. B. 2007. *Hypogene Speleogenesis: Hydrogeological and Morphogenetic Perspective.* Special Paper No. **1**, National Cave and Karst Research Institute, Carlsbad, NM.

Ollier, C. D. 1982. Geomorphology and tectonics of the Dorrigo Plateau, N.S.W. *Australian Journal of Earth Sciences*, **29** (3 & 4): 431 – 435.

Waterhouse, J. D. 1984. Investigation of pollution of the karstic aquifer of the Mount Gambier area in South Australia. In A. Berger and L. Dubertret (ed.) *Hydrogeology of Karstic Terrains: International Contributions to Hydrogeology.* **1** (1): 202-5 Hanover: Heise:

Figure 7: *Development Process Stage 1.*

Tree roots penetrate the soft limestone before the caprock forms.Photo of a quarry wall near Penola, S.A. (Photo by author)

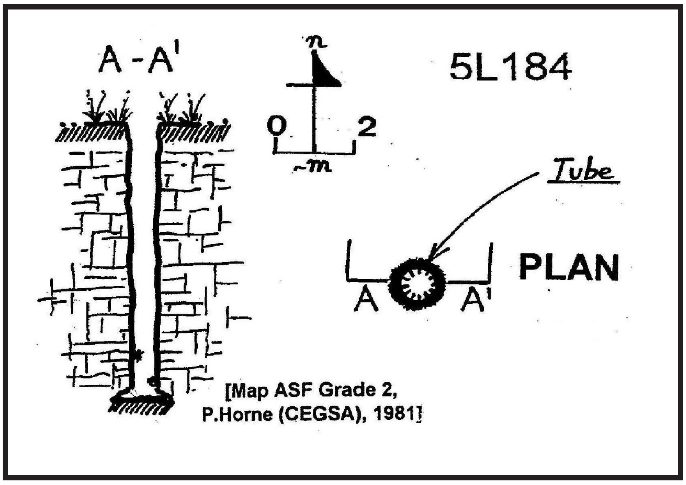

Figure 8: *Development Stages 2 and 3 Corroasion tube forms over small cavity. (Horne 1993)*

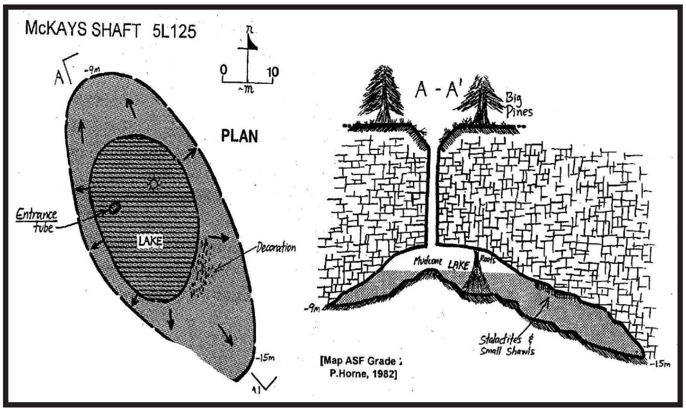

***Figure 9**: Development Stage 4. Enlargement of cavity by mixing corrosion. (Horne 1993).*

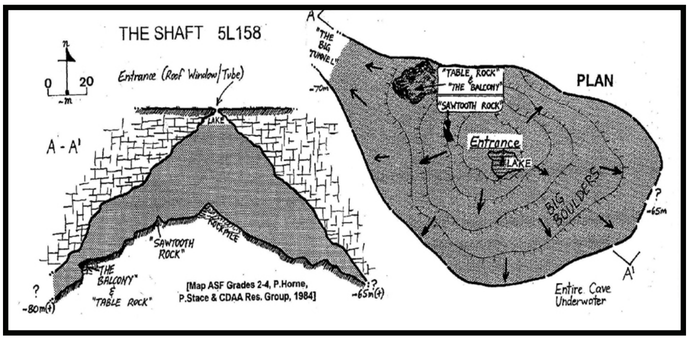

Figure 10: *Development Stages 5 and 6. Wall collapse and retreat of ceiling. (Horne 1993).*

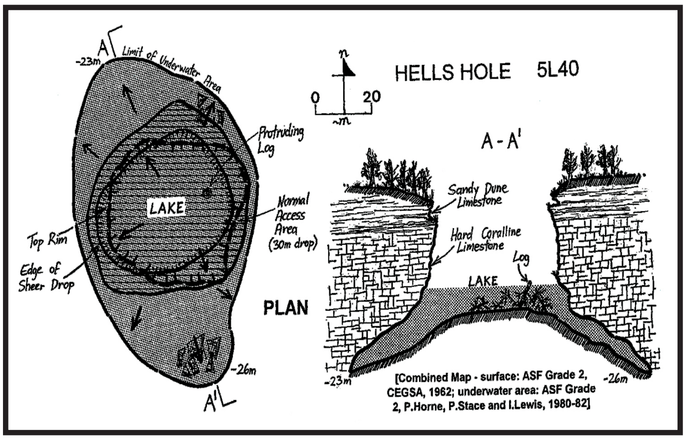

Figure 11: *Development Stage 7. Breakthrough to surface and 'cenote' formation. (Horne 1993).*