Further Hydrogeological Investigations of the Mill Creek – Kansas Creek Area, Northern Tasmania

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Abstract

Surface exploration has revealed three additional karstic streamsinks on the lower slopes of Western Bluff. All appear genetically related to Croesus Cave, but today discharge their base flow to the more recently evolved Tailender Cave Spring. This is despite the fact that one streamsink lies only 100 m from Croesus Cave. Drainage from Blue Lake, a sinkhole pond, has been traced into Rat Hole Cave, and the connection from that cave to Tailender has been confirmed. Aquaduct Swallet probably drains directly to Tailender, 345 m lower and 3.6 km distant. A major extension has also been discovered in Rubbish Heap Cave, source of the stream that discharges from Lynds Cave, but from which drainage connections to Croesus under high discharge conditions have previously been hypothesised. These data compound the evidence for the existence of a major integrated karst drainage system and a high probability of interflow between some of the components under high discharge conditions. The highest level of protective management is warranted for this very important complex.

Introduction

Ordovician limestone that crops out between the Mersey River and the lower slopes of Western Bluff (about 1400 m altitude) at the western end of the Mole Creek karst area has long been known to contain three major outflow stream caves (Figure 1). Tailender Cave (305 m altitude) lies at the upstream boundary of the limestone in the Mersey Valley and has been explored for more than 0.5 km. It appears to be the former outlet for a spring that now discharges directly into the bed of the Mersey River outside the cave, but the cave itself now serves as an overflow conduit. Just under 1 km down the Mersey Valley lies Croesus Cave (305 m altitude) in which 2 km of passages have been mapped, many of which are of large size and spectacularly decorated with speleothems, notably flowstones (Photo 1). This cave discharges about 10 m above river level and is the largest of the three outflow caves, despite the fact that under normal flow conditions it contains by far the smallest stream. Lynds Cave (290 m altitude) lies a further 650 m down the Mersey Valley, and presently contains the largest underground stream. It is also a spacious cave and has been explored for more than 1 km.

This paper reports new investigations of karst in the area: water-tracing experiments in the Tailender Cave – Croesus Cave area; investigation of the water chemistry and related aspects of Croesus Cave; and the exploration and mapping of a major new extension in Rubbish Heap Cave, source of the stream that flows through Lynds Cave.

The complex of caves in this locality is of major significance for a variety of scientific, recreational and aesthetic reasons. It is an excellent example of a major integrated karst hydrogeological system comprising various components at different stages of evolution. This complex of caves is important for the major insight it offers into the evolution of the surrounding landscape and patterns of past climatic change. Some of the caves contain evidence of multiple phases of sedimentation and re-elaboration, probably over hundreds of thousands of years, that are related to phases of relative instability and stability in the surrounding landscape during late Cainozoic glacial and interglacial climatic stages (Jennings 1967; Kiernan 1984, 1990a; Spate and Holland 1990). Radiometric dating and stable isotope analysis of stalagmite samples from Lynds Cave have also produced a sensitive record of temperature change over the period 12 600–2 800 years BP (Goede and Hitchman 1983). More recently Goede and Vogel (1991) have analysed variations in trace element composition in another dated stalagmite from this cave and have shown that trace elements can also provide important information about environmental change. These records are of intrinsic interest and of relevance to current concerns regarding possible warming of the planet by the Greenhouse Effect. Study of more recent cave sediments is providing information relevant to a better understanding of natural hazards in karst areas, such as the sudden formation of cover collapse sinkholes (Kiernan 1989b, 1990b; Kiernan *et al.* 1993). Rimstone pools in Croesus Cave have been singled out as outstanding examples of this type of speleothem (Jennings 1971, 1985). More recently discovered clastic speleothems in Rat Hole Cave are of national significance (Kiernan 1989a) while the whole area has recently figured prominently in an international text on karst hydrology (Kiernan 1992). The caves are also an important recreational venue, their possible potential for development for tourism having long been recognised.

Protection of these various values demands an adequate understanding of the cave catchments since caves are continuously interactive with water and many of the natural processes within them need the

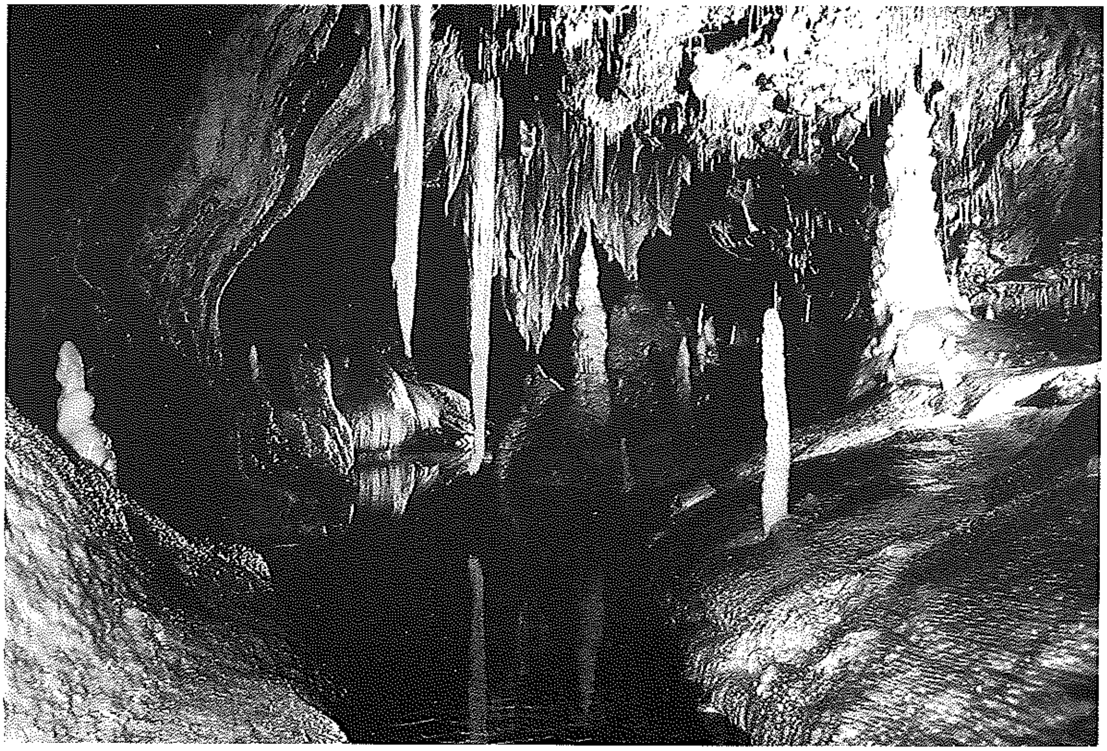

Photo 1. Speleothems in Croesus Cave. (Photo: Andrew Briggs)

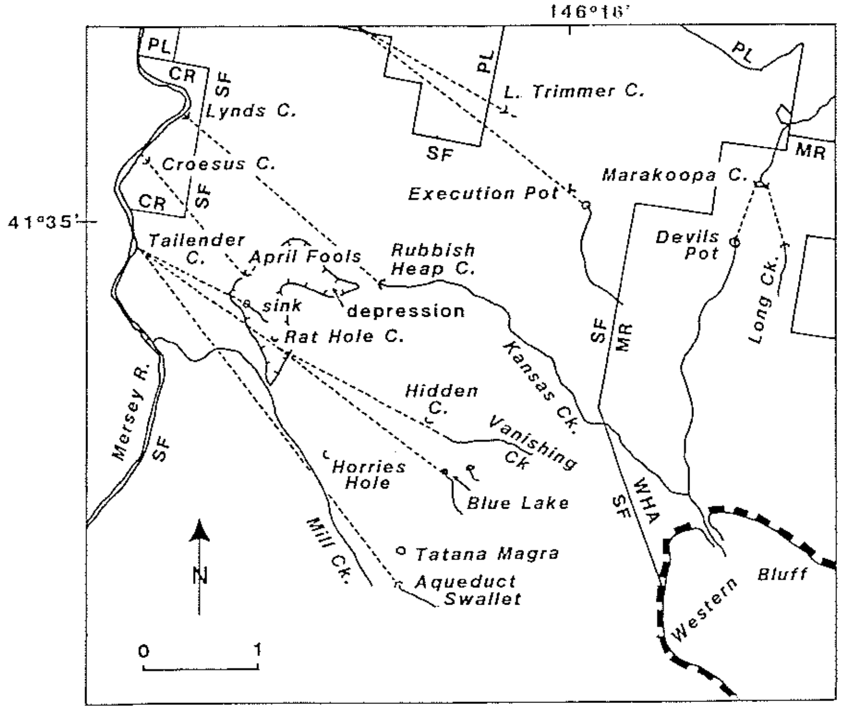

Figure 1. Relationships between karst phenomena and baseflow underground drainage routes demonstrated by water-tracing experiments. The present land tenure in the area is superimposed: CR = Croesus Cave State Reserve; SF = State forest; WHA = World Heritage Area; MR = Marakoopa Cave State Reserve; PL = private land.

maintenance of natural stream and seepage flow regimes and water chemistry. Determining drainage routes in karst areas is not straightforward since underground streams commonly ignore the dictates of the surface topography, sometimes sinking underground into inaccessible cave systems to rise again in another valley altogether. Hence, valleys conspicuous on air photographs and maps often give a totally misleading impression of the drainage. Catchment disturbance, vandalism in the caves, the impact of careless visitors underground, the theft of stalactites and other speleothems, and public safety, are among the issues that demand management responses (Kiernan 1984, 1989c; Spate and Holland 1990).

Land tenure and conservation status

In 1972, the Croesus Cave State Reserve was proclaimed over the outflow entrances of Croesus Cave and Lynds Cave. However, it covered barely one-third of either cave, the remainder of the area overlying those caves, the other caves in the complex, and all the cave-stream catchments being State forest that had been subject to logging in the 1940s to the 1960s (Figure 1). The entire catchment was included on the Register of the National Estate in September 1984. A study of karst in the Mole Creek area undertaken by the Forestry Commission, Tasmania, in 1983–84 recommended a major extension to the reserve, the establishment of Forest Reserves around the streamsink caves, and riparian protection measures, but to date none of the reserve proposals has been implemented. Part of the upper Kansas Creek catchment was included within the Tasmanian World Heritage Area (WHA) in 1988, above a bifurcation of the stream high on Western Bluff from which the northern anabranch descends into the tourist cave in the Marakoopa Cave State Reserve. The WHA boundary extends southwards along the crest of Western Buff. The catchment of Lynds, Croesus and Tailender Caves was recommended for inclusion in the WHA in a report by the Department of Parks, Wildlife and Heritage, Tasmania (Dixon 1990). The total area was recommended for protection in the report of the Balanced Panel of Experts compiled during the Forests and Forest Industry Strategy process (Podger *et al.* 1990) and has the status of Deferred Forest under the *Public Lands (Administration and Forests) Act 1991.*

Despite the presence of a gate on the outflow entrance to Croesus Cave where the Department of Parks, Wildlife and Heritage had for many years sought to administer an access permit system, two other unmanaged entrances on State forest continued to allow access. Gates were placed across these entrances by the Department of Parks, Wildlife and Heritage, with assistance from the Forestry Commission, Tasmania, in 1990. A map of Croesus Cave was prepared for the Forestry Commission, Tasmania, by P. Jackson that year as part of the Tasmanian Karst Atlas project which is being funded by the Tasmanian Forest Research Council. The Forestry Commission, Tasmania, also commissioned a major management study of Croesus Cave (Spate and Holland 1990). Some minor in-cave management works were undertaken in Croesus Cave, in 1992–93. This involved some cleaning of muddied speleothems, litter removal and the marking of desirable access routes to reduce inadvertent damage being caused by visitors.

Study of cave sediments undertaken in collaboration with the Australian Nuclear Science and Technology Organisation at Lucas Heights, New South Wales, has recently added to earlier circumstantial evidence that past logging activity has led to water chemistry and sediment flux changes injurious to some of the caves and natural values of the karst system generally (Kiernan *et al.* 1993). This evidence of adverse impacts in the caves from activities on the surface has highlighted the need for improved understanding of drainage relationships in the area.

Underground drainage

This study focusses on an area bounded in the north by the catchment of Kansas Creek, to the south by the catchment of Mill Creek, to the east by Western Bluff and to the west by the Mersey River. A further pronounced valley, formed by Vanishing Creek, descends from Western Bluff between Kansas Creek and Mill Creek. All the water that flows into this area sinks into the limestone, with the exception of Mill Creek which, at about 380 m altitude, flows onto older non-carbonate rocks that underlie the limestone. This geological boundary cuts off any underground drainage down the lower Mill Creek Valley. It probably deflects towards Tailender Cave any seepage that has occurred into the limestone further upstream along the Mill Creek Valley.

The most conspicuous surface karst feature in the area is a large compound, enclosed depression or uvala of about 0.8 km^2, closed below about 395 m altitude. This uvala is broadly U-shaped and comprises two principal axes and numerous smaller sinkholes. The northern axis continues the westward orientation of the Kansas Creek Valley downstream of the point at which that stream sinks into the limestone via Rubbish Heap Cave. This axis terminates 850 m beyond Rubbish Heap Cave in a sinkhole that contains two further cave entrances, April Fools and Top Hole, that give access into the upstream end of Croesus Cave. The southern axis of the uvala is a narrow corridor 100 m wide that extends 1100 m north-westward from just above the point at which Mill Creek flows off the limestone. It originates as a fossil stream channel formed on the northern margin of an alluvial fan deposited by Mill Creek, while downstream it also converges on the upstream area of Croesus Cave.

The relationship between Croesus Cave, the axes of the uvala and the valleys that descend from Western Bluff suggest that all these streams have at various times contributed water to Croesus Cave. This is consistent with the presence of fossil sediments in Croesus Cave that indicate it has previously contained a large and vigorous stream, and with the very large dimensions of the main stream passage in that cave. However, the present day drainage patterns in the area are far more complicated than the surface topography suggests.

Previous studies (Kiernan 1984, 1989c, 1992) have shown that Vanishing Creek, which sinks at about 530 m altitude, travels via Rat Hole Cave to the Tailender Spring. The stream that discharges from Lynds Cave has been shown to originate from Kansas Creek, which sinks into Rubbish Heap Cave (400 m altitude) at high stage, or into the creek bed several hundred metres upstream, and up to 20 m higher than the cave when the stage is lower. Rubbish Heap Cave is generally blocked by clastic debris about 50 m inside its entrance, precluding exploration of the passages that extend towards Lynds Cave. Despite a relatively modest gradient of only about 46 m/km over the linear distance of 2.4 km between Rubbish Heap Cave and Lynds Cave, the tracer flow-through time under high stage conditions when the drainage connection was proven implied a staggering water velocity of more than 2000 m/hr, much faster than any of the rates recorded in the contemporary international texts on karst hydrology by Jennings (1985) and Ford and Williams (1989). This suggested the existence of a major, large and open, cave passage in the hitherto unexplored part of this system.

Given the absence of any major surface stream to account for the stream now present in Croesus Cave, it has been assumed to originate from percolation water and gradual release from groundwater storage in glacial, colluvial and alluvial sediments that locally mantle the limestone. The entrance to Rat Hole Cave is located in the central part of the southern axis of the uvala. In recent years, the discovery of several hundred metres of previously unknown passage of impressive dimensions has facilitated access to an underground stream passage and water-tracing experiments utilising this cave. It was derisively named by its original explorers for its constricted and tortuous upper level passages that were the only part of the cave known for several decades. The discovery that the Rat Hole stream drained to Tailender was unexpected, given that Rat Hole lies in the uvala only a few hundred metres distant from April Fools and Top Hole. The main passage of Tailender Cave carries water only under high flow conditions. An older, upper level passage contains large dolerite boulders in a matrix of silt and clay. The active stream flows through a conduit a few metres below the level of the main passage and has been entered but not fully explored by cave diving (P. Cover, pers. comm.). Both Croesus and Lynds Caves are characterised by large suites of fossil clastic sediments, often embedded in speleothem carbonate that has been subjected to considerable paragenetic passage modification since its deposition. The Tailender system appears to be progressively pirating water that previously flowed to Croesus Cave (Kiernan 1984, 1990c).

Implicit in the genetic relationship between the caves that these facts imply is the possibility of older, higher level flow-path interconnections between the present baseflow conduits being reactivated under conditions of high stream discharge when the capacity of the presently evolving channels is exceeded. This is a consideration of major management significance since it means the various caves cannot be managed as if isolated from one another and a more holistic approach to catchment management is demanded.

Further investigations

In 1990, Northern Caverneers Inc. (1990) undertook further investigation of part of this area under contract to the Forestry Commission, Tasmania, as part of the Karst Atlas project. One of the principal objectives was to determine the drainage implications of limestone areas mantled by non-carbonate surficial sediment that lay upslope of the main streamsinks. A second aim was to investigate the little known Mill Creek which flows to the Mersey River at the extreme southern margin of the limestone outcrop. Due to the limited likelihood of human access being gained into cave entrances in these two localities because of probable partial blockage by slope deposits, those areas had not previously been the subject of serious scrutiny by recreational cavers, despite their fundamental importance for management of the popular caves downslope. The previous dearth of exploratory effort was also influenced by the fact that the *Middlesex* geological map sheet did not indicate the boundary of the limestone accurately, a point not detected until photogeological mapping was undertaken by C.H.C. Shannon some years ago.

Two previously unrecorded major streamsinks were located during the investigations by Northern Caverneers Inc. Blue Lake is a sinkhole pond 50 m in diameter a few hundred metres south of Vanishing Creek. No negotiable cave entrance was found there. Small sinkholes are also present 200 m to the north-east, together with another very small streamsink. Aquaduct Swallet lies at about 650 m altitude in a valley tributary to the putative main branch of Mill Creek, the latter proving to carry a very much lesser flow than the swallet. The cave was named for the remains of an old timber aquaduct that had been established to channel water across the sinkhole in which the cave is located and into the main Mill Creek Valley a short distance away to provide a supply to a sawmill that formerly operated near Rat Hole Cave. Planned further exploration and mapping was frustrated by fallen trees which blocked the cave entrance. Nevertheless, the discovery of Aquaduct Swallet was of major significance since it confirmed rumours of a cave close to Mill Creek and it represented the first major streamsink to be found between Vanishing Creek and the southern boundary of the limestone outcrop. Its presence also implied that the limestone extended further south than was indicated on published geological mapping for the area. Aquaduct Swallet also lay at a higher altitude than any other streamsink in the Mole Creek karst, about 345 m above any potential outflow and hence possibly being one of the deepest cave systems in Australia.

In January 1993, a party of Sydney cavers from the Australian Speleological Federation discovered, and partially explored and mapped, a major extension to Rubbish Heap Cave. This cave is normally blocked by the clastic and organic debris which gives the cave its name. The debris includes sawn timbers that are suggestive of past logging activity having contributed to this blockage. The party managed to excavate a way past the choke and explored a major passage, surveying as they went but turning back after 0.5 km due to a shortage of time. At the point from which they retreated, they were in a large chamber, with no indication of the passage closing down. Unfortunately, remobilisation by the stream of the debris in the entrance chamber twice sealed the extension again before exploration and mapping could be completed. Shortly afterwards, a party from Northern Caverneers Inc. located a deep natural shaft on the flank of the hill a short distance upstream of Rubbish Heap Cave, presumably descending into the conduit system associated with the watersinks in the bed of Kansas Creek upstream from the cave. These developments were of particular significance since they confirmed the presence of a negotiable cave passage in this area if access could be gained through the debris choke.

Water-tracing experiments

In order to clarify some of the drainage relationships, three water-tracing experiments were undertaken: one using fluorescein as a tracing agent in the area of upstream Croesus Cave when stream discharges were at a moderately high level in November 1992; and two others using rhodamine WT from Aquaduct Swallet and fluorescein from Blue Lake (with assistance from members of Northern Caverneers Inc.) during Easter 1993. Stream discharges were low at the time, with no water flowing in the accessible part of Tailender Cave.

The first test investigated the destination of a small stream that sinks within 100 m of the known upstream end of Croesus Cave. At 20:30 hrs on 23 November 1992, 500 g of fluorescein was injected into the stream just upstream of its sinking point. Despite periodic inspections of Lynds Cave, Croesus Cave and the Tailender Spring over the next two days, no visual evidence of fluorescein was obtained. However, an activated charcoal detector obtained from Tailender Spring on the morning of 25 November 1992 produced an elutant that fluoresced strongly in natural light. The elutant from detectors retrieved from Croesus Cave failed to reveal any sign of fluorescein under either natural or ultraviolet light. From this result it was concluded that despite the close proximity of April Fools and Top Hole, which lie in the same closed depression as the tested streamsink, the tested stream instead flows 1 km to Tailender Cave under the discharge conditions that prevailed at the time.

In the second experiment, 750 g of fluorescein was injected into a re-entrant into which water flow was visible on the margin of Blue Lake at 17:45 hrs, 9 April 1993. Monitoring was by periodic water sampling and charcoal detectors at the outflows from Tailender Spring, Croesus Cave and Lynds Cave, and in Rat Hole Cave. Pre-test samples were also obtained as controls for the fluorometric analyses. The creek in Rat Hole Cave became strongly coloured by fluorescein at some time between 20:00 hrs, 9 April 1993, and 23:30 hrs, 10 April 1993. The Tailender Spring became coloured by fluorescein after 17:15 hrs, 12 April 1993, and before (but probably not long before) 08:15 hrs, 13 April 1993. It remained strongly coloured until after 09:00 hrs, 14 April 1993. Hence this experiment demonstrated that the Blue Lake stream joined Vanishing Creek upstream of Rat Hole, and it confirmed the drainage connection between Rat Hole Cave and Tailender Spring previously reported (Kiernan 1984).

In the third experiment, one litre of rhodamine WT was injected into Aquaduct Swallet at 16:30 hrs on 9 April 1993. No visual observations of rhodamine WT were made at any site, possibly due to masking by fluorescein. Fluorometric analyses of water samples retrieved from Tailender Spring at 08:15 hrs, 13 April 1993, indicated the possibility of some tracer being present while strongly positive results were obtained from samples obtained from the spring at 08:00 hrs, 14 April 1993, and on 17 April 1993. A sample from a sump pool at the upstream end of Tailender Cave itself on 18 April 1993 also proved strongly positive. Charcoal detectors retrieved from Tailender Spring on 14 April 1993 and 20 April 1993 also tested strongly positive. These results demonstrated that Aquaduct Swallet formed part of the catchment of Tailender Spring and confirmed that the stream conduit that today feeds the Tailender Spring remains connected to Tailender by older passage systems.

Given the close proximity of Aquaduct Swallet to the southern boundary of the limestone outcrop, it seems probable that it follows passages developed just inside the margin of the limestone mass where subsurface drainage is deflected towards the Mersey River by the barrier of non-carbonate rocks. Leakage into such a system may account for the generally very modest discharge down the surface channel of Mill Creek, the surface water being perched on dolerite-rich surficial sediment that mantles the limestone beneath the valley floor. Whether some of the Aquaduct Swallet water may travel to Tailender via Rat Hole remains open to question. No rhodamine WT was observed in this cave at any time. A water sample obtained from Rat Hole on the evening of 9 April 1993 revealed no trace of rhodamine and analysis of the elutant from a detector retrieved from the Rat Hole stream at 23:30 hrs, 10 April 1993, also proved negative. Some response in the rhodamine wavelength was obtained from a detector retrieved at 15:00 hrs, 11 April 1993. However, comparison of the discharge estimates for Vanishing Creek and the Blue Lake stream, both of which are known to reach Rat Hole, with the discharge of the stream in Rat Hole

Table 1. Discharge estimates for streams, 9–12 April 1983 (by velocity head method).

Stream	Date	Time	Discharge (litres/sec)
Aquaduct Swallet	9 April 1993	16:30 hrs	9.4
Blue Lake stream	9 April 1993	17:45 hrs	4.7
Vanishing Creek	12 April 1993	14:30 hrs	1.6
Mill Creek (old mill site)	9 April 1993	18:30 hrs	1.6
Rat Hole stream	10 April 1993	11:30 hrs	7.1
Tailender Spring	10 April 1993	13:30 hrs	18.9
Croesus stream (outflow)	11 April 1993	09:50 hrs	2.4
Lynds stream (outflow)	11 April 1993	09:20 hrs	56.6

at the time the test was conducted (Table 1) suggests those two streamsinks alone are virtually sufficient to account for the Rat Hole stream. Allowance must also be made for other minor contributions that are probably also made to the Rat Hole stream by seepage waters and presumably also the tiny flow that goes underground near the entrance of Horries Hole. If any water from Aquaduct Swallet does reach Rat Hole Cave, it can only be a very minor anabranch of the Aquaduct Swallet stream rather than its total discharge.

The results of this water tracing indicate that Vanishing Creek and the Blue Lake stream utilise essentially the same systems of cave passages to reach Tailender Spring rather than travelling via separate conduits. However, they imply that most of, if not all, the Aquaduct Swallet water travels to Tailender via a separate system from that which contains Vanishing Creek and the Blue Lake stream. Whether the stream that sinks near April Fools travels independently to Tailender or joins the Rat Hole stream can only be speculated upon at this stage. Given that it sinks in the same closed depression as that in which Rat Hole is situated, its confluence with the Rat Hole stream might seem probable. However, geographical proximity and surface geomorphology can be misleading as shown by the fact that in this area reliance upon them would lead to the erroneous assumption that both the unnamed streamsink and the Rat Hole stream ought to be flowing to Croesus rather than Tailender.

Flow-through times determined during these experiments are presented in Table 2, together with the mean velocities indicated. For comparative purposes, the data derived from the tests performed in 1984, when discharge of the stream was greater, are also presented. It should be noted that the mean gradient figures are inevitably misleading since many of the stream systems probably descend steeply close to their streamsinks, with the remainder of the conduit being at a gradient very much lower than the mean. For example, Top Hole comprises a shaft system that descends essentially vertically for more than 40 m, and the mean gradient of the Croesus Cave streamway over the remaining 1.1 km linear distance to the cave outflow is probably no more than 30 m/km, and considerably less if the meandering of the stream passage is taken into account. The nature of the conduits plays a major role in conditioning flow-through times and water velocities, deep pools in particular serving to slow the flow. Despite the very steep gradient of the northern anabranch of Kansas Creek between Devils Pot and the Marakoopa Cave outflow, the flow-through time and implied velocity were slow compared to those in the lesser gradient conduits between Rubbish Heap Cave and Lynds Cave, albeit at higher discharge.

Discussion and conclusions

These hydrological studies and cave explorations have provided important new

Table 2. Flow-through times and minimum stream velocities indicated by water-tracing experiments.

Segment	Distance (km)	Gradient (m/km)	Discharge	Time (hr:min)	Velocity (m/hr)
Un-named swallet trace 1992					
swallet – Tailender	1.2	54.2	moderate–high	< 35:30	> 31
Aquaduct trace 1993					
Aquaduct – ?Rat Hole?	2.2	127.3	low	> 31:00 < 46:30	< 71 > 47
Aquaduct – Tailender	3.6	95.8	low	> 85:30 < 89:30	< 42 > 40
Blue Lake trace 1993					
Blue Lake – Rat Hole	1.7	150.0	low	> 2:15 < 29:45	< 756 > 57
Blue Lake – Tailender	3.4	94.1	low	> 71:30 < 84:30	< 46 > 40
Vanishing Creek trace 1984					
Vanishing Ck. – Rat Hole	1.6	156.3	moderate	> 3:45	< 427
Vanishing – Tailender	3.2	98.4	moderate	> 4:30 < 27:30	< 711 > 116
Kansas Creek (southern anabranch) trace 1984					
Rubbish Heap C – Lynds	2.4	45.8	high	1:10	2181
Kansas Creek (northern anabranch) trace 1990					
Devils Pot – Marakoopa	0.7	200.0	moderately high	5:00	140

insights into the karst hydrogeology of the area between Kansas Creek and Mill Creek, and proven the existence of a complex system of groundwater divides beneath the uvala when low discharge conditions apply. In broad terms, the results reinforce the evidence for genetic inter-relationships between the three drainage systems that today focus on Tailender Cave, Croesus Cave and Lynds Cave, and the critical importance of the Rat Hole system if the complexity and evolution of the system is to be fully understood. The limestone in this area is folded along axes that trend broadly NW–SE, and previous studies had shown this to be the predominant direction of underground drainage as subsurface conduits were developed along the strike of the limestone beds. The drainage in this direction is contrary to what might be predicted from the topography of the land surface, three underground breaches of surface drainage divides being involved. Glacial meltwaters, as well as local runoff, may have contributed to the genesis of cave passages in this area. The sequential development of the three outflows has been attributed to progressive incision by the cave streams as downcutting by the Mersey River has lowered the base level to which the systems drain, and more direct and efficient flow routes evolved in response (Kiernan 1990c). The results presented in this paper are consistent with this hypothesis. In particular, the position of the subsurface drainage divide between the Tailender and Croesus systems now demonstrated under low discharge conditions highlights just how close the relationship remains between these two systems. However, the new results place in question earlier conclusions that the Croesus Cave stream originates primarily as diffuse seepage into the uvala at the upstream end of the cave (Kiernan 1984, 1989c; Spate and Holland 1990).

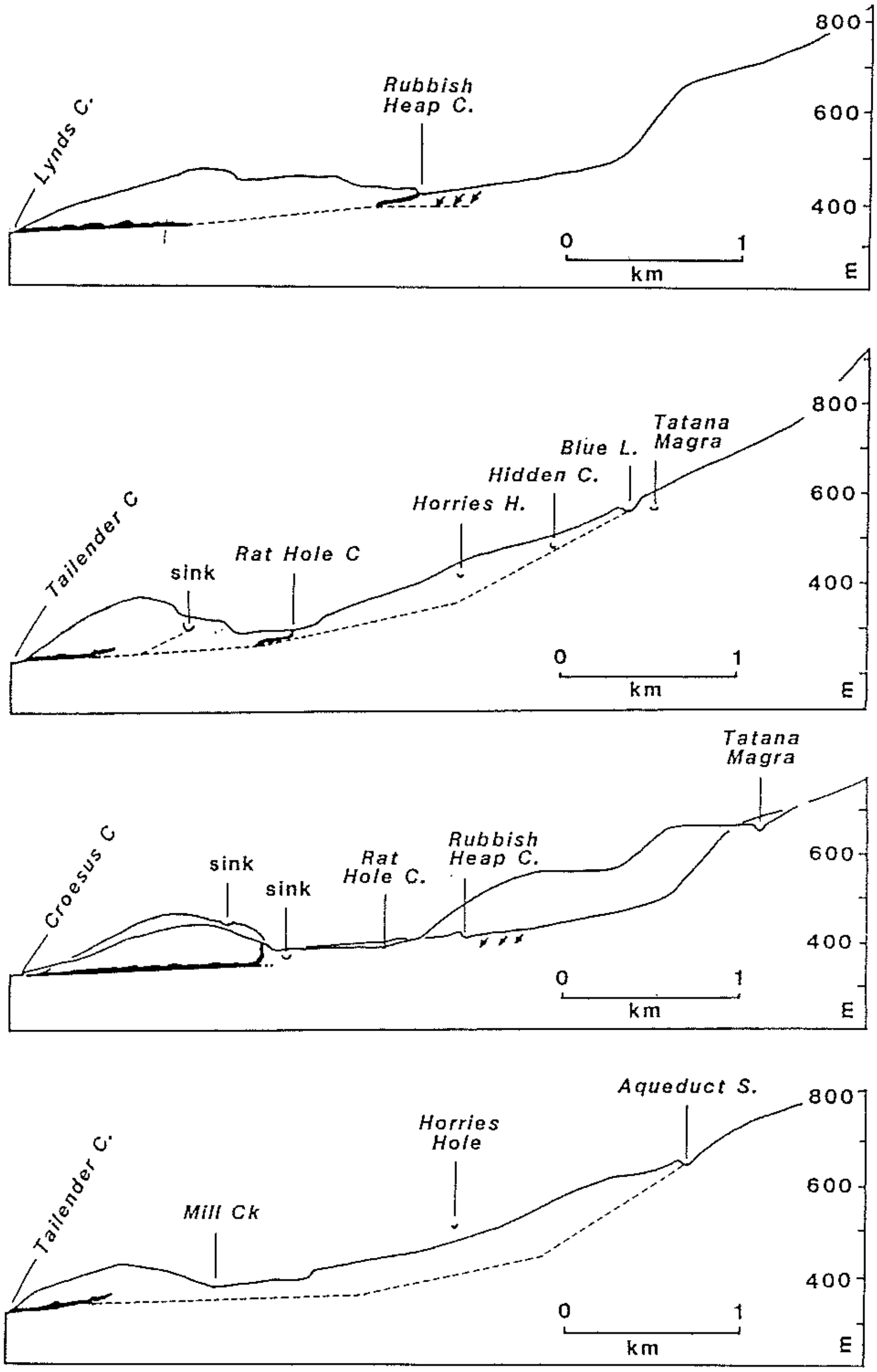

Figure 2. Developed topographic profiles indicating the relative altitudes of components of the karst drainage systems. The extent of negotiable caves discovered and physically explored to date is represented schematically, together with the potential extent of hitherto unexplored caves implied by water-tracing results.

Table 3. Altitudinal differences and linear distances between cave entrances within subsystems of the Croesus Area karst hydrogeological system.

Cave entrance	Altitude (m)	Cave entrance	Altitude (m)	Distance (km)	Altitude diff. (m)	Gradient (m/km)
From:		*To:*				
Aquaduct Swallet stream						
Aquaduct	650	Tailender	305	3.6	345	95.8
Aquaduct	650	Rat Hole	370	2.2	280	127.3
Tatana Magra						
Tatana Magra	630	Tailender	305	3.6	335	93.1
Tatana Magra	630	Rat Hole	370	3.6	270	75.0
Blue Lake stream						
Blue Lake	625	Tailender	305	3.4	320	94.1
Blue Lake	625	Rat Hole	370	1.7	255	150.0
Rat Hole	370	Tailender	305	1.6	65	40.6
Vanishing Creek						
Vanishing Creek	620	Tailender	305	3.2	315	98.4
Vanishing Creek	620	Rat Hole	370	1.6	250	156.3
Hidden Cave	600	Rat Hole	370	1.5	230	153.0
Hidden Cave	600	Tailender	305	3.1	295	95.2
Horries Hole	500	Rat Hole	370	1.0	130	130.0
Horries Hole	500	Tailender	305	2.6	195	75.0
Rat Hole	370	un-named sink	370	0.65	0	0
un-named sink	370	Tailender	305	1.2	65	54.2
un-named sink	370	April Fools	380	0.2	10	50.0
Croesus						
April/Top	380	Croesus	305	1.25	75	60.0
Kansas Creek (southern anabranch)						
Rubbish Heap Cave	400	Lynds Cave	290	2.4	110	45.8
Kansas leaks	420	Lynds	290	2.5	130	52.0
Rubbish Heap Cave	400	Bull sink	480	0.3	80	266.7
Bull sink	480	Lynds	290	1.9	190	100.0
Rubbish Heap Cave	400	April Fools	380	1.25	20	16.0
Kansas Creek (northern anabranch)						
Devils Pot	600	Marakoopa	460	0.7	140	200.0

The results reported here also highlight the fact that even though this area is already known to contain some of the most celebrated caves in Australia, considerable potential remains for further caves to be explored. The demonstrated link between Aquaduct Swallet and Tailender Cave spans a linear distance of 3.6 km which makes it the longest proven underground drainage link in the Mole Creek area (Figure 2, Table 3). The length of underground cave passage involved generally far exceeds the simple linear distance between a streamsink and resurgence. For instance, the longest cave presently known in Australia, Exit Cave, comprises some 20 km of passages developed over a linear distance of only 2.3 km between the outflow and its most distant tributary streamsink. The potential for the exploration of very long integrated caves through the

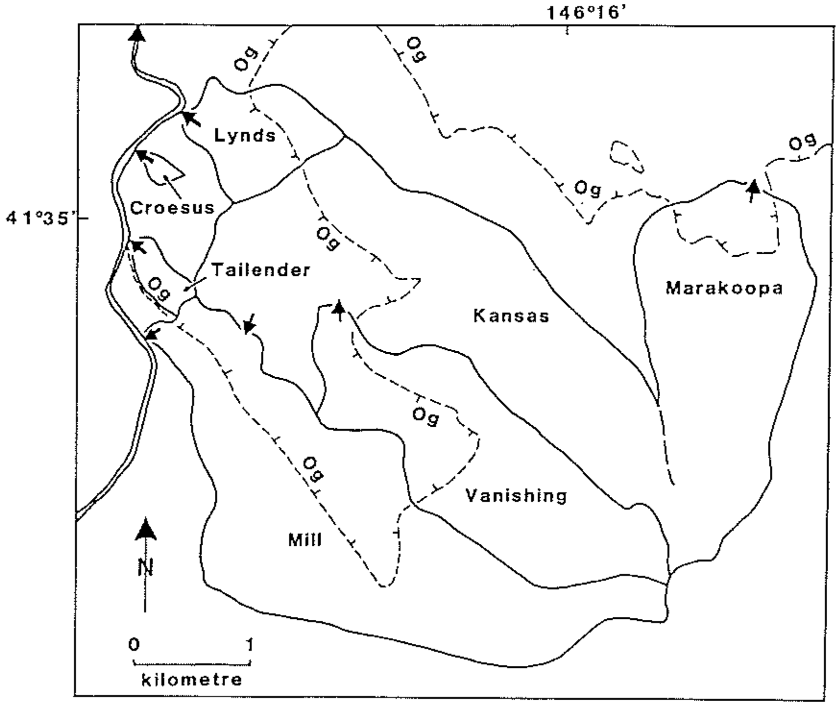

Figure 3. Stream catchments and flow routes suggested by surface contours and assumption of drainage through the lowest saddle where depressions interrupt the thalweg of a valley. Compare with Figures 4 and 5. The upslope margin of the limestone outcrop (Og) is indicated by the hatched line but is commonly obscured on the ground by non-carbonate slope deposits.

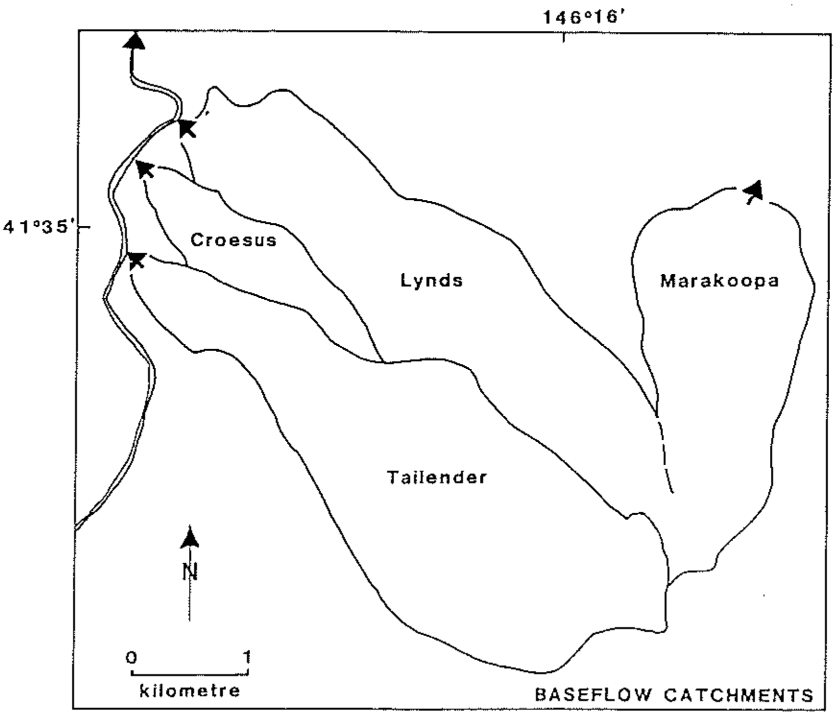

Figure 4. Baseflow catchments for the cave systems as interpreted from water-tracing experiments, geological structure and topographic factors. Compare with Figures 3 and 5.

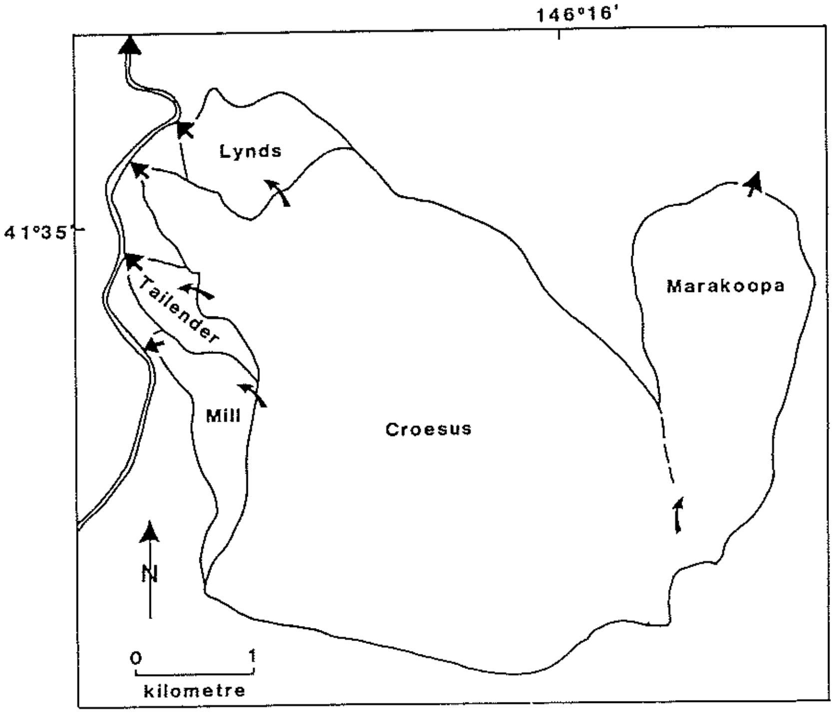

Figure 5. Catchment of Croesus Cave under very high discharge conditions. Some water from this area will also discharge via Mill Creek, Tailender Cave, Lynds Cave and Marakoopa Creek due to flow bifurcations under these conditions. The extent of the catchments exclusive to these latter streams when discharge is very high is also indicated.

linking of those parts of the complex presently known is highlighted by the genetic relationships now known to exist, including the close proximity to Croesus Cave of caves now shown to contribute their present baseflow to Tailender, and other evidence discussed later for interflow between various caves under very wet conditions. The Aquaduct Swallet – Tailender Cave system also spans a greater altitudinal range (345 m) than any other karst system in northern Tasmania (Table 3). The four deepest caves presently known in Australia are 373, 371, 354 and 323 m deep; hence, this area theoretically has the potential to reveal a cave of nationally significant depth.

Given the great nature conservation significance of the caves in this area, the very highest level of protective management is warranted. Long experience gained from around the world has made axiomatic among karst managers the absolute necessity to manage the surface catchments of any karst cave as part of the cave itself if natural values of the caves are to be safeguarded. That the surface topography cannot be used to determine the extent to which environmental disturbance in one part of this area is likely to have deleterious effects elsewhere was already evident from the demonstrated subsurface breaches of surface drainage divides (Figures 3, 4). However, while the karst hydrological investigations previously reported cast some light upon the probable juxtaposition and extent of the underground stream catchments, they involved only low discharge conditions. Given the close genetic inter-relationships between these three outflows that is now evident, it is probable that fossil connections between these three discharge systems persist and could be reactivated under very high discharge conditions when the capacity of the newer conduit systems is exceeded. Hence, from a land management perspective, they cannot be managed in isolation from one another.

Accurate determination of underground drainage routes under high discharge conditions can be difficult due to access being precluded by flooded passages. Indeed, while collecting a detector from the Rat Hole stream during earlier research in this area in 1984, one of us was forced to 'roof-sniff' back out through the main upper level passage after a pool on its floor, into which no water can be seen flowing, unexpectedly filled to within 3-4 cm of the ceiling during an absence of less than 15 minutes. The more recent work reported here has elaborated upon likely interflow processes and highlights the extent to which the adverse effects of disturbances in one area are likely to be transmitted to other areas during the types of high magnitude meteorological events that are the focus of most erosion and sedimentation in any landscape, even though some of those extended catchments may not be recognised if water tracing is done only under drier conditions. However, detailed evidence of high discharge routes underground may often be derived more safely from geomorphological considerations or progressive, painstaking cave exploration over time under drier conditions than by water-tracing experiments under pressure during floods. In open stream passages, flood pulses move as kinematic waves that travel faster than the water itself, while flood pulses through water-filled conduits move as an almost instantaneous pressure wave that travels at the speed of sound (Ford and Williams 1989): at such times there are better places for a geomorphologist or caver to be.

Interflow, possibly overland, between Kansas Creek and upstream Croesus Cave had already been invoked to explain occasional flooding of the latter cave, which in one instance has been of sufficient magnitude to tear out the gate on its outflow entrance (Kiernan 1984). Were it not for the intervention of Rubbish Heap Cave, Kansas Creek would flow to the lowest part of the uvala axis adjacent to April Fools, the present surface divide between the streamsink and uvala being no more than 5 m high. Given the location of the subsurface divide between the Tailender and Croesus systems demonstrated in the present study, the nature of the cave passages and the constraining topography at that point, interflow between these two systems under very high discharge conditions now seems inevitable. A report from a local resident of the main road having been cut in August 1970 by flooding of the depression between Rat Hole and upstream Croesus (Rod How, pers. comm., 22 April 1990) provides one instance in which such interflow must have occurred. Whether this might have involved bifurcation of Mill Creek around either side of an alluvial fan in its middle reaches also warrants consideration, since the local catchment may otherwise have been too small to generate a surface flow of this magnitude. The valley in which Rat Hole occurs originates as a fossil surface channel that extends from the apex of the alluvial fan and down its northern flank. Further evidence of overland flow into upstream Croesus Cave is provided by a 1.8 m thick bed of rounded gravels in a sandy matrix that occurs on the wall of a sinkhole adjacent to the April Fools entrance to Croesus Cave. A cave entrance in that sinkhole can be penetrated by humans for only a short distance but could easily accommodate a substantial flow of water. Approximately beneath this point in Croesus Cave lie ascending cave passages that are apparently clean-washed and associated with one of at least three upstream tributaries of the Croesus stream. Hence, at very high stage, much of the catchments of Kansas Creek, Tailender Creek and Mill Creek probably contributes water to Croesus Cave (Figure 5).

The speleothems in Croesus Cave are extremely sensitive to water flow and water chemistry conditions. There has been mechanical damage to some of the rimstones by bedload gravels transported in recent decades by the stream that previously deposited finer chemical sediments instead. There has also been an evident change in the chemistry of the stream water from conditions that facilitated construction of the rimstones to more aggressive water that is now dissolving the rimstones away (Spate and Holland 1990). Both imply significant changes in the regime and chemistry of the stream in recent decades. Logging and roading are the only major disturbances that have occurred in the catchment. Thus, it would be extremely unwise to risk compounding these changes. In delicately poised karst systems, the potential exists for natural system thresholds to be crossed thereby triggering an evolution towards the establishment of a new equilibrium that may run its course long after the original disturbance has ceased to play any direct part. Comparative isotopic studies of recent cave sediments have also added to the evidence for deleterious effects underground due to surface disturbance since the early 1950s (Kiernan *et al.* 1993). The streamflow regimes and water chemistry are the product not just of conditions on the limestone outcrop itself, but also in the upper catchment on the slopes of Western Bluff. High magnitude–low frequency events such as major floods are major determinants of the geomorphological character of an area and often the major agents that effect geomorphic change. Hence, it is at the time that the very high discharge extended catchment of Croesus Cave is likely to become operative that the greatest risk is posed to this remarkable complex of caves. Of additional concern is the fact that this is also the time when the upper catchments are at greatest risk of landslide activity, already a recognised geomorphic hazard confronting forest management on the Great Western Tiers, and when resultant sedimentation problems are likely to arise in the streams that flow into the caves.

These conclusions beg the question of future land tenure and management of the area. This area is the only part of the Mole Creek karst that remains forested from the cave catchments on the slopes of the Great Western Tiers to the system outflows on the Mersey River. The area became Deferred Forest because of a perceived need to obtain more information about the appropriate boundaries for protection, rather than any doubt regarding its nature conservation significance. While the area remains Deferred Forest it is potentially vulnerable to limestone quarrying at any time, to logging at some time in the future, and to other forms of activity injurious to its karst values. Most of the caves remain devoid of any form of protective management. The new investigations reported here all confirm the importance of the area for nature conservation and its susceptibility to damage, and demonstrate the need to include the total catchment in the gazetted boundaries. The area should now be formally reserved.

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