TASMANIA'S COLD CAVES:
AN ISLAND OF ALPINE KARST

Kevin Kiernan
School of Geography UTAS Private Bag 78 Hobart 7001

ABSTRACT

Unlike mainland Australia, much of Tasmania's karst is essentially alpine in character. During the most extensive of several glaciations an ice cap of over 7000 km² extended over Tasmania's Central Highlands. Glacial effects on the karst variously included the removal of surface features by glacial erosion, the clogging of pre-existing caves by glacial sediment and/or the generation of new cave passages by glacial meltwater. Away from the glaciers, other non-glacial cold climate (periglacial) effects included the destabilisation of hill-slopes when conditions were too cold to permit colonisation by the forests that now bind the slopes together; the swamping of karst surfaces by landslide and other mass movement deposits, sometimes blocking streamsinks and causing a reversion to surface drainage; interruptions to the formation of speleothems caused by changes to vegetation and/or water flow; the shattering of rock in cave entrance zones by the freezing and expansion of moisture in crevices even at very low altitudes; and an increase in the volume and size of sediment delivered into streams. Understanding Tasmania's karsts requires an appreciation of the extent to which they have been influenced by these various environmental factors. The tectonic stability of Tasmania's mountains allows the survival of very ancient alpine karst and this, together with its distinctive geographical setting, allows acquisition of evidence of global significance concerning patterns of natural climate change

INTRODUCTION

At the first ASF Conference I attended back in 1970, Albert Goede showed a stimulating map of the extent of Tasmanian karst known at that time, and it led me to devote many years to furthering the documentation of this island's karst. But after having written a few too many reviews of the extent and nature of Tasmania's karst, culminating in publication of my *Atlas of Tasmanian Karst* a decade ago (Kiernan 1995), I promised myself I would stop! So while my talk today is aimed at giving you a feel for Tasmanian karst it is not my intention to attempt any sort of comprehensive review - rather, I wish to pick up on one or two themes.

Speleos who check the net for information on Tasmania's caves soon encounter a firm warning on the web site of the local caving club that they may find caving beneath this island a little different to the conditions to which they have become accustomed elsewhere. Tasmania's caves are colder (~9°C) and wetter than those of mainland Australia, and the perils that await the unprepared range from discomfort sufficient to detract from the pleasure of a caving trip to the very real risk of potentially fatal hypothermia in the event of delay or an accident that leaves the victim immobile underground for a protracted period. I want to take this opportunity to suggest that in visiting Tasmania's caves in January 2005 you have never had it so good. Although conditions may be bracing now, they have been far more so in the past.

In virtually all karst areas, various non-karstic processes are also involved in shaping the landforms and may sometimes out-compete the dissolving of limestone, such as intense wave action in exposed coastal karsts. The thing that most distinguishes Tasmania's caves from those of mainland Australia is the importance of cold conditions, past and present. Much of Tasmania's karst is essentially alpine in character. Hence, Tasmanian caves are in stark contrast to those of mainland Australia where, if conventional geographical or ecological definitions are adopted, no true alpine karst exists (although

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"Next time, could you please hold the Conference in summer?" Michael Wasmund came prepared.

the rules of definition are occasionally bent for various reasons) (Spate and Houshold 1989).

While caves have fascinated me since I was a kid, my scientific interests were kindled more by time spent at the original Lake Pedder, a remarkable glacial landform. So despite studying caves and karst over a period of 35 years, I have probably now spent more of my time on, under and around glaciers than I have around limestone - and after five decades I still can't decide what I want to be when I grow up: caver or alpinist? glacial or karst geomorphologist? So in this talk I want to bring these two perspectives together and consider the implications of alpine conditions for the evolution of Tasmanian caves and karst.

Alpine karst is special, and not just for its often scenically spectacular setting or even the fact that it is in such areas that the deepest cave systems are able to develop. In alpine karsts the water necessary for cave formation may at times be frozen into immobility, and there may be limited vegetation to produce the organic acids that aid rock dissolution. But abundant seasonal meltwater released from snowfields and sometimes glaciers can foster rapid landform evolution. Steep hydraulic gradients foster deep phreatic looping, incised canyons and vertical shafts that require technical caving techniques. Valleys may be deepened by glacial erosion that permits energetic water circulation through evolving caves, or they may be filled with sediment causing back-flooding in karst systems and the development of new cave passages (Ford 1983, Smart 2004). Understanding our alpine karsts requires understanding the extent to which such processes have previously operated – and, because caves are often important storehouses of information about past environmental conditions, this may have much to tell us about climatic history (Goede and Harmon 1983).

Webb et al. (1992) failed to find evidence of climatically-driven influences on landscape evolution at Buchan in Victoria, and have argued that the glacial and periglacial episodes that had such a great influence on karst landscapes in the northern Hemisphere occurred in only small areas of Australia's southeastern highlands and Tasmania. However, this perhaps overlooks the magnitude of such cold climate effects on karst in Tasmania where an ice cap of over 7000 km^2 once existed in the Central Highlands, extensive glaciers also developed elsewhere, and other cold climate influences are evident down to present sea level (Kiernan 1990a).

GEOGRAPHY AND EARLY HISTORY OF TASMANIAN KARST

The geographical context of Tasmania's caves

Why should Tasmania's caves be as cold as they are? After all, at latitude 43° S Tasmania is no closer to the pole than sunny Spain or the paradise of millionaires on the French Cote d'Azur. So why are we not drifting from sun-drenched entrance to sun-drenched entrance, pausing only to pluck a few more olives or down another bottle of red? The answer lies in the marked asymmetry of climate between the northern and southern hemispheres. Heard Island, home of Australia's most remote lava caves, endures a climate that makes Iceland look tropical, yet it is located at about the same latitude as London (53°). Forests are common north of the Arctic Circle, but there are no trees south of the Antarctic Circle. People live and work at 66° N in Alaska, yet at equivalent southern latitudes we have the ice-bound coast of East Antarctica. While one can paddle happily in the ocean when the summer sun shines at 70°N on the northern coast of Alaska, at the equivalent latitude in the southern hemisphere one is well on one's way inland up the world's largest glacier, the Lambert Glacier in the Australian Antarctic Territory, which drains from the highest point of the Antarctic polar plateau.

Why should this be? Due to both the curvature of the Earth's surface and the tilt of the axis about which it rotates solar energy is received unevenly across the surface of the Earth. Atmospheric circulation resolves part of this imbalance by redistributing energy. Circulation of the oceans that cover two thirds or our planet also plays an important role but in the southern hemisphere elongate land masses form barriers to oceanic circulation. And in contrast to the northern hemisphere which is dominated by continental land masses, at southern temperate latitudes there is mostly water, and Tasmania forms an island with many thousands of kilometres of unbroken ocean stretching westwards to the Patagonian coast on the other side of the globe - little wonder that a certain amount of moisture rides the westerly Roaring Forties airstream that softly caresses our island.

Climate and the origins of Tasmanian limestones.

It has not always been as cold as it is now, partly because the Earth's land masses have not always been located in their present positions. Tasmania's limestones were deposited under both warmer and cooler conditions than exist at present - two examples of this variation should suffice.

As part of the super-continent of Gondwana drifting around on an evolving globe, the Tasmanian region lay in warmer latitudes during Ordovician times 500-434 Ma BP (million years before present), and it was there that the coral reefs that formed our principal karst-hosting rock, the Gordon Limestone, were originally laid down in a tropical environment (Rao 1989). But evidence of a later dramatic shift in Tasmania's climatic fortunes is spectacularly displayed at the entrance to Three Falls Cave in the Florentine Valley, where the steeply-dipping tropical limestone that was deposited in an environment somewhat akin to the present Persian Gulf, is overlain by near-horizontal sedimentary rocks of Permian age (~300-250 Ma BP) that instead bear comparison with those that are currently forming beneath the Ross Ice Shelf in Antarctica.

By the Permian period the Tasmanian region had drifted into polar latitudes. Present day Antarctica was still attached to Tasmania and was moored somewhere off Queenstown, such that glaciers swept across what is now Tasmania. A glacially-abraded rock pavement from this period has since been exhumed from beneath the Permian rocks at Mt Sedgewick, just upstream from the Dante karst in Tasmania's West Coast Range. Glacial sediments were deposited directly by these Permian glaciers, mostly in the western half of Tasmania, while further east melting ice-bergs rained down rocks eroded from Antarctica and western Tasmania onto the beasties living on the sea floor - fossils pulverised in this way may be seen among those in the Permian rocks at Three Falls Cave. The limestone that forms the Fossil Cliffs at Maria Island off Tasmania's east coast were deposited in these cold polar seas, and if you visit there you may see that some of the large scallop-like *Eurydesma* shells at this site have similarly been blitzed by ice-berg bombers. In contrast to the Ordovician limestones, there are few caves in these relatively impure Permian limestones, the largest being near Gray in NE Tasmania and the sea cave Tear Flesh Chasm near the Fossil Cliffs.

When did caves start to form?

Once limestone is exposed in a terrestrial setting, karst commences to develop. The best-documented of Tasmania's palaeokarst occurs at Eugenana in northern Tasmania where limestone quarrying many years ago revealed ancient caves filled with sediments. Examination of spores in the cave sediments revealed species that were last around during the middle Devonian (~380 Ma BP), implying that the caves had been present for at least that long. The cave sediments also told a further important story: while the limestone is intensely folded, the cave sediments remained horizontally-bedded, implying an episode of mountain building prior to the caves being formed. Hence, these caves provided evidence for the age of one of the most important phases of mountain building in Tasmania's geological history (Banks and Burns 1962). Parts of some cave systems may be even older, and caves have probably also been forming ever since – although the present form of the best known Tasmanian caves is very much younger. Such antiquity of some karst elements is not particularly unusual - cave development at Wombeyan, NSW, also began in the Devonian (Osborne 1993).

The landscapes in which these events unfolded were vastly different to those that exist today – indeed some of the most important rocks that dominate Tasmania's topography today were yet to be formed. After the Permian glaciers vanished from Gondwana great thicknesses of river and lake sediments accumulated. Subsequently, in Jurassic times (~204-131 Ma BP) a vast amount of molten magma was intruded in between the horizontal bedding of these sedimentary strata, where it spread out between them like the ham in a rock sandwich. This magma cooled to form the dolerite that is now widespread. Over subsequent aeons the upper slice of "bread" was eroded away, leaving the harder dolerite "ham" capping the mountains - herein lies the explanation for the dolerite cap and tabular form of many mountains in eastern Tasmania.

These rock sequences were subsequently riven by fractures and faults generated by earthquakes that raised or lowered various blocks relative to others. Combined with progressive incision by eroding rivers, this left the underlying limestones exposed along the sides of valleys and hills where acidic runoff from the dolerite summits began to form karst where limestone was exposed, at places like Mole Creek, Junee-Florentine and Ida Bay. Minor remnant evidence of very early karstification is to be seen in some of these places - just as many karsts in mainland eastern Australia have also experienced a phase of karstification in the Tertiary prior to their burial under gravels or basalt (Osborne & Branagan 1988).

Climate and karst in the more recent past.

We now come to the cold origins of Tasmania's present caves. At the commencement of the Tertiary (~65 Ma BP) Australia, Antarctica and South America were still joined and the first two were covered in rainforest – despite the fact that Tasmania lay 2500 km south of its present position. But after ~45 Ma BP the northward drift of Australia broke the connection between Tasmania and Antarctica, hence oceanic circulation was altered. The new Antarctic Circumpolar Current began to form a barrier that prevented warm water from lower latitudes reaching the Antarctic coast, conditions cooled and glaciation was initiated virtually simultaneously in Antarctica and Tasmania prior to 30 Ma BP in Oligocene times. The only place on Earth outside Antarctica where this onset of glaciation in southern polar regions is recorded is just upstream from the Lorinna karst in northern Tasmania (Macphail et al. 1993). Significantly, the glacial sediments at this site lie close to the bottom of the Forth River Valley, implying that this valley already existed and that recognisable elements of the landscape in which our present crop of karst and caves were to evolve were now becoming recognisable. By analogy with the Forth Valley, it seems probable that some of Tasmania's other major valleys were also in existence by this time and that the limestone in some of these areas had already been exposed to karstification.

A sequence of sediments that overlie limestone in the Linda Valley in western Tasmania highlights the magnitude of environmental change implied by such rapid cooling (though not necessarily the same event) and its implications for karst development. At Linda alluvial silts were deposited by a stream that carried fine sediment particles that had been produced primarily by chemical weathering that occurred when the vegetation cover maintained slope stability and generated organic acids that decomposed the rocks, a situation highly conducive to karst formation. The silts contain pollen of rainforest species now found only in New Guinea and New Caledonia but also once present in Antarctica, and a fossil soil that formed on the silts contains fragments of wood related to the present-day Tasmanian celery top pine. But the stability implied by this soil terminated when a great influx of gravels was dumped by a stream that carried chunks of rock that had been prised from surrounding slopes by strong physical weathering in a cooler environment where little vegetation remained. The entire sequence was then over-run by a large glacier at a time when an ice cap of over 7000 km^2 covered Tasmania's Central Highlands. Limestone at Linda was buried beneath a vast thickness of glacial sediments, as was other karstified limestone in the Queen and King valleys, and elsewhere (Kiernan 1990a, 1995). Tasmanian karst had now assumed an alpine aspect.

COLD-CLIMATE PROCESSES IN TASMANIA'S ALPINE KARSTS

Over the last 3-4 Ma global climate has repeatedly cooled during what are termed Glacial Climatic Stages and then re-warmed during Interglacial Climatic Stages such as we have been experiencing for the last 10 ka (10 000 years). The implications of these episodes of cold climate for Tasmania's evolving caves have been profound. There are three principal types of specifically cold-climate processes that operate in alpine karsts - glacial and glacio-fluvial processes, p*ara*glacial processes and p*eri*glacial processes. Each has been important in Tasmania. A brief explanation of these terms is warranted before we continue.

Glacial (including glaciofluvial) processes

Glacial processes are those that are the direct consequence of glaciers eroding away rock or depositing sediment. *Glaciofluvial* processes involve erosion or deposition by the liquid melt-water that is generated on, within and at the margins of glaciers. A variety of different impacts of these processes are evident in Tasmanian karsts.

All glaciers are made of ice, but not all ice is the same. In continental interiors conditions may be so cold that ice sheets remain frozen to the ground and the flow of ice downslope is permitted only by internal deformation and slippage between ice crystals. Under such circumstances, glaciers are unlikely to erode away much pre-existing karst or to pick up much sediment that can later be deposited elsewhere. Conversely, in more temperate mountain settings closer to the sea as in western Tasmania the ice is commonly a little warmer so that meltwater is able to exist within and at the base of the glaciers, enabling the ice to slide on a film of water, ripping out pieces of the underlying rock which are then frozen into the glacier base thus converting slippery ice into highly abrasive sandpaper. Glaciers of this kind erode more efficiently than continental glaciers, thus picking up more rock fragments and hence depositing more sediment downstream, either as *moraines* (well-defined ridges) or just sheets of *till* (glacial sediment). They also generate considerable volumes of meltwater which carry silt and gravel which are ultimately deposited as *outwash sediments.* Depending on particular circumstances meltwater streams may block caves with sediment, or, alternatively, carrying just enough sediment to equip the water with highly abrasive tools that allow the streams to rapidly enlarge developing caves and hugely expedite cave evolution. Between these two extremes - stifling or enhancing cave formation - are many shades of grey (Ford 1983, Ford and Williams 1989).

The meltwater drainage systems within a temperate glacier are themselves highly karst-like. Water flows across the ice surface to streamsinks that typically form at the intersection of joint systems (such as incipient crevasses) and flow through tunnels within and beneath the ice mass that are enlarged by flowing water and particularly by air currents (Kiernan 1993). Most of Tasmania's major rivers once originated from such melt-karst systems, such as the 70 km-long Derwent Glacier (Kiernan 1985, 1990a). These were probably the biggest cave systems ever present in Australia, but the organisers of this conference have thoughtlessly scheduled it thousands of years too late for you to take a look-see. Sometimes meltwater streams carve channels into the bedrock beneath the ice, as in Tasmania's King Valley (Kiernan 1981). The 30 m-deep limestone gorge through which the Dante Rivulet flows was probably formed partly as such a basal meltwater channel. Where the underlying rock is limestone, the pseudokarst hydrology in the glacier is superimposed on the true karst hydrology. The additional hydraulic head in the glacier can pump water more energetically through the karst beneath the ice than would otherwise be the case (Kiernan 1993). The best-documented cave of this kind is Castleguard Cave in the Canadian Rockies, which penetrates beneath the Columbia Icefield with passages ascending to the base of the glacier - the entire cave has at times been entirely over-ridden by ice, and it contains a stygobitic fauna that appears to have survived at least one such ice age in the sanctuary of the cave (Ford 1983).

No previously-glaciated karst occurs on mainland Australia but at least 53 separate Tasmanian karst areas are known to have been glaciated (Kiernan 1995). In some cases relatively recent glaciers have left fresh moraines, as at Lake Sydney and Dante Rivulet. Aerial photographs suggest various other likely glaciated karsts in areas that have never been visited by cavers, such as the Erebus-Denison area where large depressions occur at ~850-950 m altitude (Kiernan 1995). Care is required because closed depressions don't have to be karstic - they can also be caused by glacial processes, such as the melting of blocks of ice within glacial sediments.

However, it would be very wrong to assume that the karst now present in an area that has previously been glaciated is necessarily somehow the product of past glaciation. In many cases present-day karst features in some glaciated areas have probably developed since the glaciers vanished and have no direct relationship to patterns of glacial erosion or of meltwater flow. For example, the Vale of Belvoir karst is heavily mantled by glacial sediments that are pock-marked by sinkholes, many of which are water-filled. Whether the sinkholes have formed since the glaciers vanished or represent flushing of old pre-glacial karst since the ice retreated is an open question but palaeomagnetic dates suggest a pre-Pliocene age for the till (Augustinus and Idnurm 1993), suggesting ample time has elapsed for karst features to have formed since deglaciation. The sinkholes at Carbonate Creek in the upper Franklin River catchment and in various other areas are probably also entirely postglacial, with any glacial influence restricted to that caused by the thickness of the surface sediments and its impact on postglacial karst processes.

Paraglacial processes

It is now time to introduce a potentially confusing but important term. *Para*glacial processes involve various non-glacial processes that have been conditioned by prior glaciation (Ryder 1971, Church and Ryder 1972). They include the adjustment of slopes left in an unstable condition as the climate warmed and glaciers retreated. Hence, steep rock walls tend to relax, crack open and sometimes collapse once the glacier that eroded them vanishes and ceases to support them (Blair 1994). Joints produced by this unloading of valley sides can also provide a focus for water to penetrate and initiate caves, but the same process can result in caves inside the valley wall being destroyed by large-scale collapse, as appears to have occurred in the Timk Valley at Mt Anne. Similarly, moraines that were originally deposited against glacier margins and left unsupported when the ice withdraws often collapse and are washed away to form new alluvial deposits - but which bear an imprint of past glaciation. Much of this change occurs fairly soon after the ice or glacier retreats but before conditions have re-warmed sufficiently for forest to re-establish and help stabilise slopes.

Recognition of material originally emplaced by glaciers can become complicated when the material is redistributed by paraglacial landslides or when stream action reworks it into alluvial fans. The problems increase when the glacial sediments are ancient because a variety of additional processes are likely to have also intervened and given the material many characteristics of non-glacial processes. Hence, while it has been argued that a glacier once flowed down the Leven Valley to near the present coast (Colhoun 1976), large alluvial fans formed by streams re-working old glacial sediments are more prominent at ~60-100 m altitude at the Gunns Plains karst ~18 km upstream than are moraines - material more clearly of glacial origin remains intact at ~450 m altitude ~27 km further upstream at the Loongana karst, but fresh moraines are found only above 900 m altitude in the uppermost headwaters on Black Bluff. Context is all important when seeking to interpret old deposits.

Periglacial processes

Another group of cold-climate processes have nothing to do with glaciers but have confusingly been termed periglacial processes (note: *peri* not *para*) because they were first described from cold environments near the margins of glaciers. Periglacial processes can occur only on unglaciated surfaces. They persist today in high mountains and glacier-free polar areas, but they influenced a much greater proportion of the globe during the Glacial Climatic Stages when climatic conditions reduced the vegetation biomass allowing wind, water and ice much greater access to the ground.

Periglacial processes include the physical breakdown of rocks by processes such as frost shattering whereby moisture that penetrates into fractures expands upon freezing. Even close to sea level on the lower Franklin River, angular rubble was frost-wedged from the roof of caves such as Kutikina and Deena Reena, both before and during the time Aborigines sought shelter there during the most recent phase of intense cold ~15-20 ka BP (Kiernan et al. 1983). The resulting shattered rubble is moved down hill-slopes by a variety of processes, which leads to streams carrying coarse cobbles away from the mountains rather than the fine sands, silts and clays mostly carried today when vegetation covers the slopes and contributes to organic acids that chemically decompose rocks. During colder times the forest biomass in Tasmania was much less than now, slopes were exposed to intense physical weathering and were prone to various forms of slope instability which as Goede (1973) has demonstrated in the Junee area were sometimes sufficient to block streamsinks and caves and force a reversion to surface drainage.

Freezing of the ground, either long-term (permafrost) or diurnally, is another typical periglacial process. There are obvious implications for cave and karst development if the supply of liquid water needed to dissolve limestone is shut down by freezing. This phenomenon, coupled with vegetation changes, may underlie the observation that speleothem growth tends to slow or halt in temperate alpine regions during Glacial Climatic stages, as Goede and Harmon (1983) have demonstrated in Tasmania. Seasonal or diurnal thawing of ice in the ground may saturate the soil and allow it to flow downslope, a process that is particularly effective if there is permafrost at depth because the melted liquid cannot penetrate the permafrost and becomes perched on its surface, elevating pore water pressures beneath the thawed ground. There is evidence for only limited permafrost in Tasmania, but seasonal freezing and resultant slope instability was widespread. Cave development may be particularly focused downstream from large snowdrifts that release meltwater (Ford and Williams 1989).

Periglacial processes likely effected only a small handful of karsts in the highlands of southeastern Australia such as Wombeyan, Yarrangobilly and Cooleman Plain (Jennings 1967, 1985; Gillieson et al. 1985), but periglacial phenomena have now been recorded from 198 Tasmanian karsts.

Other cold-climate impacts beyond the mountains

Sediment swept down-valley from the highlands by seasonal meltwater streams inundated the evolving karst in some lowland valleys. By this means the effects of cold climate were felt in many karsts even well-removed from the mountains. Given evidence of periglacial processes once occurring down to present sea level in Tasmania (Colhoun 1977a,b) it is likely that few if any karsts escaped significant periglacial impacts - hence even some of our coastal karsts have an alpine aspect. As in all other parts of the world, karsts close to the coast were also influenced by a fall of global sea levels by up to 150 m that resulted from water being locked up in global ice-sheets and glaciers. This had the effect of steepening the hydraulic gradient through coastal karsts until sea level rose again as the climate warmed and the great ice sheets melted.

QUINTESSENTIALLY ALPINE: REVIEW AND SPECULATION ON SOME TASMANIAN GLACIATED KARSTS

Glacial erosion versus karst dissolution

One of the more conspicuously glaciated Tasmanian karsts is at Mt Anne, where a major valley glacier previously flowed 9 km down the Timk Valley, a cirque was eroded into the end of the karstic north-east ridge, and smaller glaciers formed on surrounding hills (Kiernan 1990b,c, Kiernan et al. 2004). Lake Timk lies in a large basin that is drained underground to a spring in the neighbouring Snake Valley >2 km distant - there is surface overflow from Lake Timk only on very rare occasions. As is quite common in alpine karsts, a chicken-and-egg question arises in relation to the origin of the depression.

Is it simply a typical glacially-eroded depression (cirque) from which karstic channels have since evolved? Or was it originally a sinkhole that focused glacial erosion giving rise to the present glacial lake basin? A similar chicken-and-egg issue arises in relation to some of the glacial lake basins in the Frenchmans Cap massif, some of which lie in areas where there is dolomite (Peterson 1960) that is known to contain some small caves. Might preglacial sinkholes have provided the foundation for the spectacular glacial lakes that now characterise this landscape? Combined sinkholes and cirques are also present in the Picton Range where the same question arises (Kiernan 1989a).

Karst formation beyond glacier snouts

Small moraines occur at the head of the valleys that drain into both Khazad-Dum and Growling Swallet, implying that small glaciers were once present in these locations and proglacial meltwater from their snouts previously flowed towards the caves. Jennings and Sweeting (1959) suggested that the underground course of Mole Creek was influenced by proglacial meltwater being forced to flow around the edge of large outwash gravel fans and against the bordering hill margins in which caves were developed. Proglacial meltwater has discharged onto limestone in many other areas including parts of the Precipitous Bluff karst and in the Vale of Rasselas.

Karst formation beside glaciers

Meltwater discharged from and along the sides of glaciers seems implicated in the formation of caves in several areas. The caves at Mt Ronald Cross are located broadly coincident with the margin of the former Surprise Glacier, suggesting meltwater from the ice margin may have played a role in cave location, its action perhaps focused on valley-wall unloading joints. In some cases meltwater formed caves some distance from the lateral ice edge. Meltwater discharged from the edge of a glacier that descended the Lawrence Valley from the Mt Field massif towards the floor of the Florentine Valley scoured an impressive channel through a lateral moraine of glacier-edge debris and spilled downslope to Welcome Stranger Cave, in which gravels have been deposited on at least two occasions (Kiernan et al. 2001) - the possibility exists that the cave was originally formed in this way. Moraines constructed along the sides of glaciers can also block the descent of streams from adjacent mountain slopes. A massive sinkhole on the western side of Mt Gell may be of this origin, having formed where meltwater or tributary streams were trapped behind a moraine barrier on the edge of the former Alma Glacier.

Karst formation beneath glaciers

Karst features in the uppermost Dante Valley in the West Coast Range have also been over-ridden by glaciers during even the most recent and restricted glaciation known to have occurred in Tasmania. The deep and narrow limestone gorge with occasional underground segments that has been incised down the axis of the valley probably owes its origin, at least in part, to meltwater flowing at the base of the Dante Glacier – this gorge is certainly too deep to have formed over the few thousand years since the glacier last retreated (Kiernan 1995).

Lake Sydney at Mt Bobs occupies a substantial cirque at the downstream end of which sinkholes have formed. These sediment-choked sinkholes are incapable of evacuating all the winter rains and snow-melt and hence become flooded to form an extension of the lake. The valley floor between Lake Sydney and Pine Lake is similarly mantled by glacial sediments, but tributary streams that descend from the valley walls are slowly re-excavating their way back down through glacial sediments into the pre-existing karst system (Kiernan 1989a).

Although the most recent glaciers vanished 10-16 ka BP flushing of the system has still not been achieved. This site lies at the very head of the valley hence it is likely that the system is over-ridden during each glaciation, however minor. It may be that cave development is most effective when the advancing glacier bulldozes away the sediment deposited during its previous retreat because then meltwater under the additional hydraulic head within the glacier is able to vigorously scour and enlarge the cave system. If so, this karst system may constitute a subglacial, subterranean meltwater channel - but it may be preglacial.

Multiple glaciation of Tasmanian karsts

In some cases karsts occur sufficiently far upstream in valleys that have been repeatedly glaciated that they must have been over-run during numerous glaciations. For example, the Sophia River karst was repeatedly over-run by glaciers but these caves are now lost to us beneath the Pieman River hydro-electric reservoir so we may never get to know their secrets. Similarly, the karst around Mt Cripps and in the lower Fury Valley/Mackintosh River area has been repeatedly glaciated.

In an early glaciation a glacier flowed down the Lawrence Creek Valley onto the floor of the Florentine Valley, depositing a thick carpet of glacial sediment. It seems reasonable to assume that the limestone in the Florentine Valley had been exposed long enough for karst to have evolved prior to the earliest of the glaciations. It is conceivable that the largely sediment-choked system we see today was formed during one or more interglacials – although if the present condition of the system is anything to go by interglacials may have allowed only partial flushing of sediment from the ancient system rather than an opportunity to elaborate the caves by active erosion of the limestone bedrock. More effective flushing and cave enlargement may have been achieved during glacial advances when ice did not reach the floor of the Florentine Valley but was restricted to the upper reaches of the Lawrence Valley from which torrents of seasonal meltwater were released. A similar history of caves being plugged by sediment when over-ridden by glaciers and then flushed out at other times is evident from Nelson River where the limestone is mantled by glacial sediment and remnants of glacial outwash gravels remain lodged in some passages and niches (Kiernan 1983).

Ancient glaciers and celebrated Tasmanian karsts

There are various other Tasmanian karsts that have been over-ridden by glaciers only during the earliest and most extensive glaciations. They include the karst at Forest Hills below Federation Peak, karst areas in the middle Picton, middle Huon and lower Weld valleys, at Loongana in the Leven Valley and Lorinna in the Forth Valley. But still further from the source areas where the glaciers arose are some karsts where the presence of more ancient glaciers is possible but has proven harder to confirm. But determining just how extensive the glaciers were during the most intense glaciations is important if the total extent of past interactions between glacial and karst processes is to be understood.

Confirming the former presence of ancient glaciers can be difficult because glacial sediments tend to be reworked over time into other deposits such as river gravels, or are buried by younger non-glacial deposits. The situation is further complicated by the fact that some forms of glacial sediment can appear similar in character to material deposited by some other processes such as landslides and solifluction. This has led to over-estimation of glacier extents in the past and means that the possibility of glaciation in some additional areas (eg. Moina, Hastings) is yet to be substantiated. The converse situation can also apply with former glacier limits being underestimated. For example, glacial outwash exhibits structures indicative of deposition by running water that can lead to its misinterpretation as a conventional fluvial deposit. Extensive experience in glacial environments and knowledge of the wider context of the deposits is critical to reliable interpretation.

We know that the earliest glaciations were much more extensive than those that occurred more recently, but they occurred so long ago that the distinctively glacial landforms and sediments they produced have since been reworked into other types of sediment making any glacial origins difficult to discern.

Under such circumstances the presence of glacial *erratics* (rock types that do not outcrop in an area and can only have been carried there by a glacier) offers one clue, as can our knowledge of the relative magnitude of different glaciations. If the glacial deposits close to the karst area are young then it is possible that the more extensive earlier glaciers reached it.

One means by which the relative age of glaciations has been determined has been by comparison of the extent to which glacial deposits have been weathered since their deposition. Insufficient time has elapsed for the most recent deposits to be more than minimally degraded while the oldest deposits have been significantly eroded and decomposed. Where the evidence is best preserved there are commonly fresh, intact moraines at the upper end of a valley, then older, more degraded moraines further down-valley, and finally deeply-decomposed ancient glacial deposits many kilometres further downstream. Hence, we cannot assume that the furthest down-valley recognisable moraine in any area necessarily marks the absolute limit of past glaciation - although neither should we assume that it cannot!

Junee area

As Goede (1973) correctly deduced long ago, dolerite-rich slope deposits produced by periglacial and other slope processes outside glacier limits during cold climate stages filled many pre-existing karst depressions, blocked streamsinks and forced local reversion to surface drainage in the Junee area. Where did all this dolerite originate? The dolerite summits between Tyenna Peak and Wherrets Lookout provide an ample source for the western part of the Junee area, but further east a direct glacial influence has now been recognised (Kiernan et al. 2001).

Although dolerite rubbles many metres thick overlie the limestone in the Khazad-Dum/Threefortyone Cave area, the only upslope bedrock source for all this material is a dolerite outcrop of ~0.2 km^2 at the summit of Tyenna Peak, hardly sufficient to spawn the massive accumulations downslope. Glacial features in the adjacent Humboldt Valley including moraines that extend southwards from the upper Humboldt and into the Junee area clearly demonstrate that the Humboldt Glacier overflowed onto the eastern part of the Junee karst, dumping huge amounts of glacial sediment and deflecting meltwater flows towards those places where the principal caves now occur (Kiernan et al. 2001). But that occurred long ago, and this glacial sediment has since been reworked into soliflučtates, landslide deposits and alluvial fans. Given the implied extent of past glaciers, ice and meltwater may also have spilled from the plateau and influenced cave development further west.

Florentine Valley

We touched earlier upon the impact of the former Lawrence Glacier which descended from the K-Col area behind Mt Field West onto the floor of the Florentine Valley. What other parts of the Florentine Valley might have been affected by glaciers? In the Lawrence Valley, small and fresh moraines occur for 2.8 km below K-Col while the glacial landforms 3 km further downstream are more degraded and the glacial sediment on the floor of the Florentine Valley >8 km from the valley head is so heavily reworked and deeply decomposed that we may never know just how far the glacier extended westwards when the ice was most extensive. Significantly, ice from the same source near K-Col also descended into the Garth Creek Valley which contains Growling Swallet. This implies that at the very least glacial meltwater has played a role in formation of this celebrated cave, but just how far did the Garth Glacier extend at maximum phase? As in the upper Lawrence Valley, small fresh moraines occur at the head of the Garth Valley. No older glacial deposits have been confirmed further downstream towards Growling Swallet but given the common ice source area it seems probable that earlier glacial advances in the Garth Valley would have been as proportionately larger as they were in the Lawrence Valley. Hence, it is likely that much of the dolerite-rich sediment that has buried the limestone in the lower Garth Valley was originally glacial sediment, the character of which has been greatly changed by subsequent erosion and re-deposition by non-glacial processes such as periglacial solifluction. This would imply that Growling Swallet was actually over-ridden by glaciers and that various neighbouring caves have also been points of meltwater input (Kiernan et al. 2001). Identifying the precise margin between the soliflucted glacial sediments and the non-glacial soliflucted slope deposits on the western slopes of Mt Field West may prove impossible, but concerted research in the caves may prove very profitable.

Elsewhere in the Florentine Valley small glaciers also formed on Wylds Craig during the most recent glaciation, and during the earlier, more extensive glaciations ice conceivably reached the limestone floor of the Florentine Valley in the Cole Creek area. And in the very headwaters of the Florentine River moraines extend downslope from a small cirque on The Thumbs, with outwash sediments spread across the limestone valley floor.

Ida Bay

Goede (1969) pointed out that the position and form of the D'Entrecasteaux anabranch passage of Exit Cave are consistent with its having been formed by glacial meltwater being decanted off the margin of an outwash fan and against the foot of the Marble Hill. A major moraine deposited by a glacier at least 4 km long extends down the slopes of the Southern Ranges onto the floor of the D'Entrecasteaux Valley at ~240 m altitude to within 4 km of Exit Cave. The glacial sediments are only moderately weathered, implying the likelihood that the earliest glaciers extended much further. The configuration of the Hammer Passage and the nature of the sediments it contains are somewhat similar to the D'Entrecasteaux anabranch and it is conceivable that meltwater discharged directly from an earlier, more extensive glacier may have been involved, possibly including development of a recharge point at the western end of the Grand Fissure (Kiernan 1991). But much more research on the surface sediments is required to explore this intriguing possibility.

Gunns Plains

That Gunns Plains was over-run by the former Leven Glacier is implied by the suggestion of Colhoun (1976) that a glacier once reached the Alison Golf Links ~18 km further downstream. Unequivocal evidence for glaciers having extended this far is yet to be found but several lines of evidence suggest it at least reached Gunns Plains. This evidence includes poorly-sorted deposits containing boulders of erratic rock types that do not appear to belong in the valley, some of which are so large (up to several metres diameter) that they could not have been transported by the Leven River. As at Junee the present character of the sediments is generally not glacial - most now occur in alluvial fans, suggesting *para*glacial redistribution of the original glacial sediment and/or reworking by *peri*glacial and other processes. In this case, no obvious relationship between the present caves and possible former glacier hydrology or ice margins has yet been discerned – the caves may have simply evolved since these very ancient glaciers were present.

Mole Creek

Joe Jennings first suggested back in the 1960s that glacial meltwater from the Great Western Tiers had influenced development of caves at Mole Creek (Jennings and Sweeting 1959, Jennings 1967). But was the influence of past glaciation confined solely to meltwater action kilometres downstream from any actual glacier as Jennings hypothesised?

Progress on elucidating the patterns of underground drainage at Mole Creek has been slow. Nearly two decades elapsed between the work by Jennings and my own studies (Kiernan 1984, 1989b, 1992). Then close to another two decades elapsed before any further substantial research on the karst hydrology was initiated, this time by the Tasmanian Department of Primary Industries, Water and Environment (DPIWE).

While I would anticipate that after 20 years there are bound to be some major advances on the results of my old reconnaissance-level work, I am not privy to the results of the DPIWE work, so will hazard a few comments on cold climate influences based on the earlier work.

Glacial outwash is abundant in the Union Bridge area but it does not require a glacier having reached as far as Mole Creek, only that a glacier once lay further upstream. But Eric Colhoun and Albert Goede both found deposits at two separate sites on Mersey Hill that they considered probably glacial (Colhoun 1976), and my own studies some years later suggested extensive glaciation (Kiernan 1982, 1984, 1989b). Hannan (1989) subsequently confirmed glaciation of the Croesus Cave area in his Masters thesis on glaciation of the Mersey Valley. The most recent work has revealed unequivocal glacial deposits beneath the outwash near Union Bridge. This material, known as basal till, comprises tough, preconsolidated sediment that is plastered onto the ground beneath the pressure of a glacier, and studies of its fabric (the packing and orientation of its grains) has confirmed its glacial origin.

How thick was this ice? Reworked sediments of probable glacial origin that occur on Mersey Hill would imply at least 60 m of ice over the site of the present Mole Creek township. What were its implications for the karst? While Jennings and Sweeting (1959) argued that the position of some cave passages just inside the margin of hills located beside fans of glacial outwash gravel was due to meltwater being decanted from the fans onto the hill margins, an alternative explanation now is that meltwater from the glacier base was involved - but for now this remains speculative because much more work needs to be done to explore this fascinating possibility.

It is even possible that the entire Mole Creek area was totally buried beneath a massive thickness of ice. Sediments that contain material that may originally have been glacial occur far downstream to beyond the Railton karst, 15 km north of Mole Creek. If these sediments are truly paraglacial it would imply Mole Creek having been very deeply buried by ice with Mt Roland standing as a nunatak above the glaciers – but paraglacial reworking of the sediments and serious errors in published geological maps do not help to resolve matters (Kiernan 1982).

CONCLUSIONS: THE SIGNIFICANCE OF TASMANIA'S ALPINE KARST

Many Tasmanian karsts are essentially alpine in character. Cold-climate processes have influenced the character of most Tasmanian karst areas, a substantial number of which have been glaciated. Some of Tasmania's most celebrated caves are among those influenced by past glaciers. These alpine karsts are of great scientific interest.

From a scientific standpoint, the greatest importance of Tasmania's alpine karst lies in its tectonic setting, its antiquity and its geographical location. While alpine karst is relatively common worldwide, it typically occurs in areas of active mountain-building where a rapid pace of development and destruction limits the potential for survival of ancient alpine karst. For example, in New Zealand's Southern Alps there has been over 18 000 m of uplift during the last 3 million years, sufficient to raise Mt Cook to twice the height of Everest had not erosion outpaced the uplift. In contrast, the relative stability of Tasmania's mountains allows the survival of very ancient alpine karst. This highlights the capacity of Tasmanian caves to provide evidence of global significance concerning patterns of natural climate change over a very long time scale.

Palaeokarst phenomena are to be anticipated virtually anywhere pure limestones have been exposed to karstic processes prior to the present erosion cycle, but the topographic context has often been quite different to the present. Hence, in the best known alpine karst in Europe, Vercors, karstic pockets filled with weathered soils are associated with Eocene fold structures, but the relief remained moderate during the Miocene and remnant karst features are now disconnected, truncated or unroofed. Precursors of the deep cave systems such as Gouffre Berger did not appear until after 5-6 Ma BP with development of the largest and highest levels of major cave systems developed only in the last 1.5 Ma (Audra 2004). But the Forth Valley near the Lorinna karst was already exposed when glaciation first gripped the Antarctic region 30 Ma BP - this is the only place in the world outside Antarctic where this onset of Antarctic glaciation is recorded. By analogy with the Forth Valley, its seems likely that many other Tasmanian valleys in which karst is exposed have also existed in their present form for a very long time. In this sense, the great antiquity of the Australian continent is replicated in Tasmania's alpine karsts, but at the same time the vigorous alpine processes that have shaped some of the world's most celebrated karsts in more recent and rapid time are also present here.

We must also consider the important geographical location of Tasmania. The climatic asymmetry of the Earth means that the climatic histories that have been compiled from northern hemisphere evidence are not necessarily applicable to the southern hemisphere. Because southern temperate latitudes are mostly oceanic there are few locations where terrestrial evidence of climate change can be obtained. The paucity of karst in the Patagonian Andes and the rapid tectonic uplift of both that area and New Zealand's Southern Alps limits the length of the record that is ever likely to be obtained.

Uplift compounds the difficulties entailed in inferring past climate because glacier extent during different glaciations may owe more to the height of mountains at the time than to the magnitude of truly regional climate severity at southern temperate latitudes. Hence, the stability and antiquity of Tasmania's alpine karsts means that studies of their sediments, both above and below ground, is helping provide understanding of events that are of global significance, based on evidence that can be obtained from nowhere else on Earth. ■

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