EARTH SURFACE PROCESSES AND LANDFORMS, VOL. 21, 453–466 (1996)

NICKPOINT RECESSION IN KARST TERRAINS: AN EXAMPLE FROM THE BUCHAN KARST, SOUTHEASTERN AUSTRALIA

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Received 22 June 1993
Accepted 4 July 1995

ABSTRACT

Nickpoint recession in the Buchan karst, southeastern Australia, has resulted in the formation of an underground meander cut-off system in the Murrindal River valley. Three nickpoints have been stranded in the surface channel abandoned by the subterranean piracy, and these can be correlated with river terraces and epiphreatic cave passages in the nearby Buchan River valley. The presence of palaeomagnetically reversed sediments in the youngest cave passage in the Buchan valley implies that the topographically lowest nickpoint in the Murrindal valley is more than 730 ka old, and the other nickpoints are probably several million years old. The nickpoints are occasionally active during floods, but the diversion of most surface flow underground has slowed down their retreat to the extent that they have been effectively stationary for several million years

Underground nickpoint migration has been by both incision within major phreatic conduits and their abandonment for lower-level passages. The nickpoints are all present in the upstream part of the cave system, but have not migrated past the sink in the river channel, despite the long period of time available for this to happen. The sink is characterized by collapsed limestone blocks; these filter out the coarse bedload from the river channel. As a result, erosion within the cave passages is dominantly solutional and therefore slower than in the surface channel, where it is mostly mechanical. In addition, to transmit a drop in base level the cave system requires the removal of a larger volume of rock than for the surface migration of a nickpoint, because any roof collapse material in the subsurface system must be removed. These factors have slowed the migration of the base-level changes through the subsurface system, and may be a general feature in caves that have diffuse sinks as their main inputs.

KEY WORDS nickpoint recession; karst geomorphology; cave development; Australia

INTRODUCTION

Nickpoints are abrupt changes in the gradient of a river long profile, and are usually represented by a waterfall or rapids. They often form as a result of the lowering of the river's base level, and are therefore key factors in deciphering the history of erosion surges and overall denudational development of river systems. Studies dealing with nickpoint migration in karst terrains have generally been concerned with the effects of base-level lowering on karst evolution and cave development (e.g. Warwick, 1960; Droppa, 1966; Smart, 1986; Palmer,1989). There has been little investigation of the actual mechanisms of subsurface nickpoint migration, apart from a generalized review of the possible modes by Ford and Williams (1989). This neglect reflects, to some extent, the lack of modern fluvial studies of nickpoints in bedrock channels, as well as the difficulties of access to underground systems.

However, in karst landscapes subterranean piracy across the neck of an incised river meander will form a cave system that may bypass a nickpoint. Such a system offers an excellent opportunity for studying the relationship between nickpoints and cave development. Only a few meander bypass caves have been

CCC 0197-9337/96/050453–14

described, e.g. Sof Omar Cave, Ethiopia (Ford and Williams, 1989; Worthington, 1991), London Bridge, eastern Australia (Jennings *et al.*, 1976), and their relationship to nickpoints has not been documented. Along the Murrindal River, in southeastern Australia, three closely spaced nickpoints in the surface channel are closely associated with the underground bypass system which has developed at the site, and can also be related to surface landforms along the neighbouring Buchan River valley. This area therefore offers an ideal opportunity to explore the interactions between cave development and nickpoint migration, and also gives insights into the possible limits to the rate of subsurface nickpoint migration.

SETTING

Regional geology

The Buchan area is a small enclosed karst terrain (Figure 1), bounded to the west, north and east by rhyolitic ignimbrites of the Snowy River Volcanics (see Webb *et al.* (1991) for a more detailed discussion). The Early Devonian calcareous Buchan Group comprises three units: the Buchan Caves Limestone, the Taravale

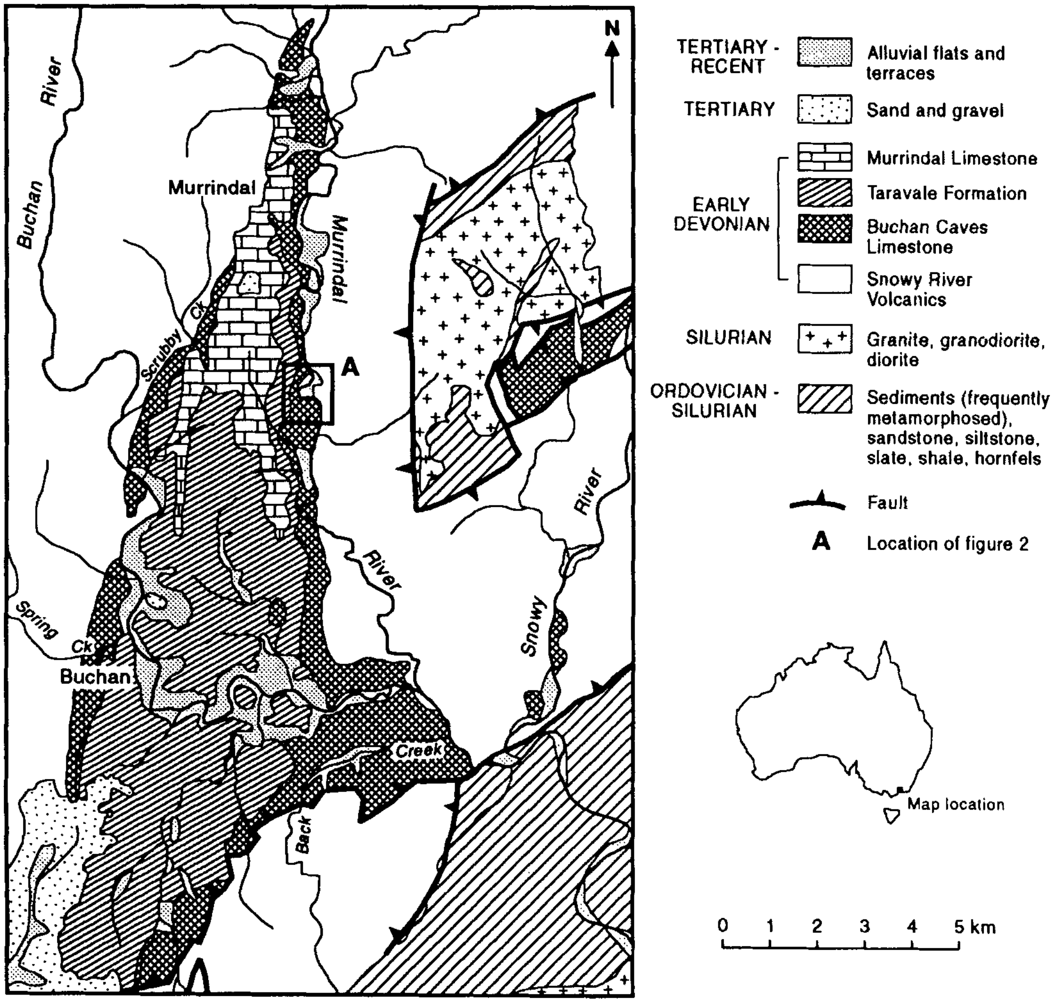

Figure 1. Location of the study area and the main elements of the bedrock geology

Formation, and the Murrindal Limestone. The Buchan Caves Limestone consists mostly of thick-bedded, relatively pure limestone. It conformably overlies the Snowy River Volcanics and is in turn overlain by the Taravale Formation, which consists of thin-bedded calcareous mudstones. The Taravale Formation interfingers with the Murrindal Limestone, which outcrops only to the north of Buchan and merges northward with the Buchan Caves Limestone, as the lower part of the Taravale Formation lenses out.

Surface geomorphology

The main drainage of the Buchan area is provided by the southerly flowing Buchan and Murrindal Rivers, both of which have their headwaters in the Snowy River Volcanics (Figure 1). Both rivers flow in bedrock channels and have a very coarse bedload dominated by boulders and cobbles.

Lithology and structure significantly affect the alignment of these rivers and their valley forms. At Buchan, the southward-flowing Buchan River emerges from a V-shaped valley cut into the volcanics, and then crosses the more easily eroded Taravale Formation of the Buchan Group (Figure 1). Here, lateral erosion has outstripped vertical incision, resulting in the formation of a broad valley containing a suite of thee distinct paired bedrock terraces. These lie at consistent heights above the present river channel (2·5–3·5 m for the lowest terrace, 8·5–11 m for the middle, and 28 m for the highest (Webb *et al.*, 1992). Each terrace can be correlated with a horizontal epiphreatic cave level in the extensive Dukes cave system along Fairy Creek, a tributary of the Buchan River (see Webb et al. (1992) for a complete description). Downstream from Buchan, the Buchan River turns towards the east and then flows through another steep-sided valley, in this case cut into the Buchan Caves Limestone, before it meets the Murrindal River and then the Snowy River. The confluence of the Buchan River with the Snowy River marks the limit of the carbonate sequence (Figure 1) and acts as local base level for the Buchan area.

The Murrindal River flows more or less north–south, and much of its course approximately follows the contact between the Buchan Caves Limestone and the Snowy River Volcanics (Figure 1). The valley cross-section is markedly asymmetrical, reflecting the structural control imposed on the valley morphology by the shallow westerly dip of the boundary between volcanics and limestone in this area (Figure 2a). The eastern side of the valley is a low-angle dip slope floored by volcanics, and formed by sliding of bedrock slabs down this slope into the channel. Along the opposite (western) valley wall are steep limestone cliffs. Because the Murrindal does not flow through any easily eroded units like the Taravale Formation, its valley is generally narrow, and there are only a few small river terraces which all occur upstream of the area of interest (Pyramids Hill), and do not shown any consistent elevation above the river.

Pyramids Hill lies within an incised meander on the Murrindal River 6 km upstream from the junction of the Buchan and Murrindal Rivers, and rises up to 140 m above river level (Figure 2a). It consists of strongly jointed Buchan Caves Limestone, dipping gently westwards. Steep limestone cliffs have formed on the northern and eastern sides of the hill, adjacent to the river. Within the broad, open, dry valley to the west of the hill are several collapse dolines, the largest of which, Dalley's Sinkhole (M-35), leads into a cave system described below (Figure 2a and 2b). Subterranean piracy across the neck of the incised meander around Pyramids Hill has occurred, so that an underground drainage system takes all the discharge of the Murrindal River except during flood events. Water enters the subsurface system through a series of diffuse sinks in the river bed, spread over a distance of probably 100 m. The sinks are for the most part covered by the well-rounded cobbles and pebbles that characterize the bedload material of the surface channel. The downstream (main) sink is a collapse doline floored with large limestone blocks, and is developing into a blind valley. A small cave is present in this doline (Figure 2a; described below), but it cannot be traversed through to the main cave system because of collapse.

The boundary between the limestone and the underlying Snowy River Volcanics crosses the Murrindal River on the northern side of Pyramids Hill (Figure 2a). As a result, the river bed where the sinks occur is underlain by limestone, but on the eastern side of Pyramids Hill the Murrindal River has a bedrock channel cut into volcanics. Between the main sink and the resurgence, where the cave stream emerges and flows into the river, the channel is dry except during high-flow events, and contains three distinct steps, all cut into volcanics (Figure 2a and 2b). Each of these represents a nickpoint, and they are

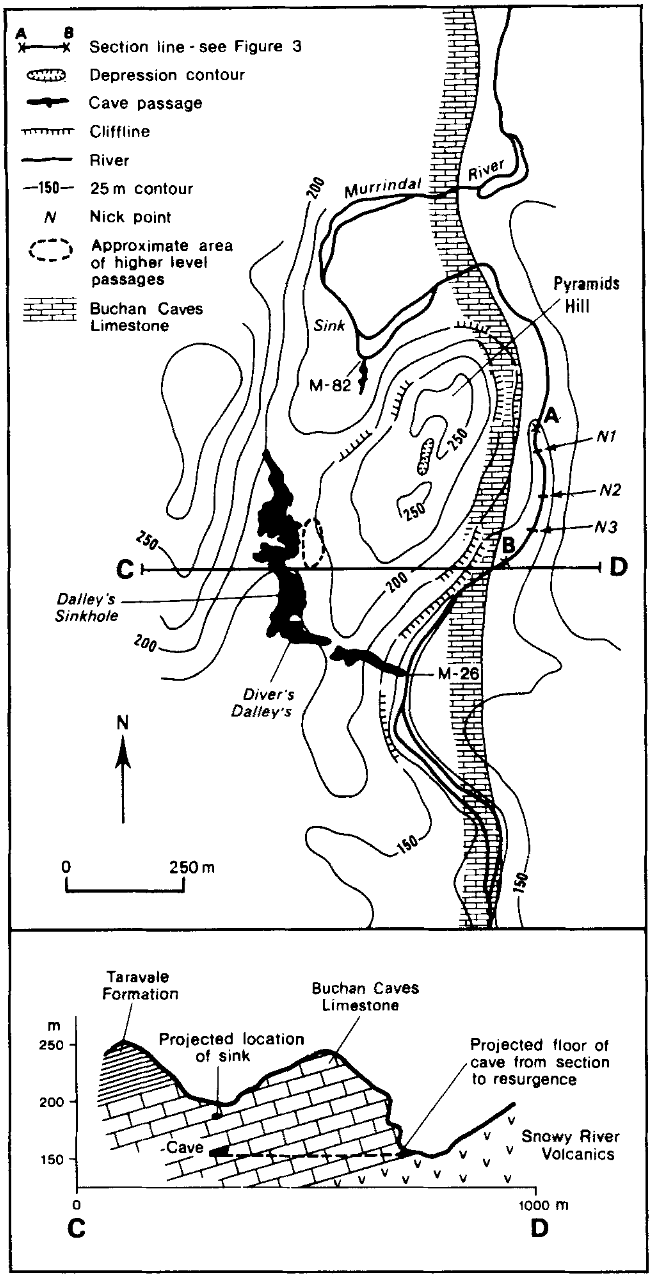

Figure 2a

separated by short horizontal stretches of channel. The heights of the lips of the individual nickpoints above the downstream channel are 2·7, 12·3 and 27·2 m (Figure 3). The bedrock channel between the nickpoints is generally clear of coarse sediment in its steeper parts, except locally in potholes. The largest potholes occur just upstream of the first nickpoint and may be the result of increased energy within the 'drawdown reach' (Gardner, 1983) of the nickpoint. At the first nickpoint, high-flow events are concentrated into a narrow, 4 m deep channel on the western side; this channel has apparently migrated by breaching the upstream walls separating neighbouring potholes. However, flood debris indicates that the whole width of the channel at the nickpoint is active at times of very high flow.

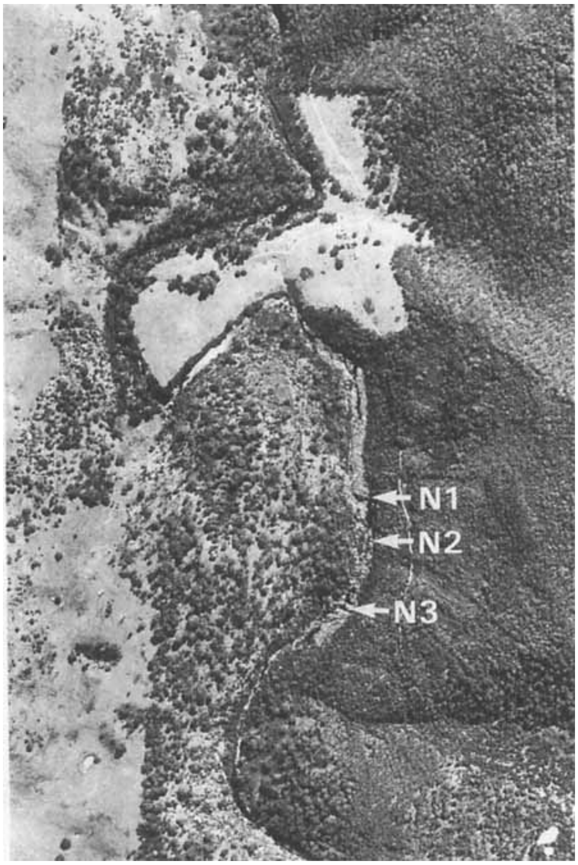

Figure 2. Surface and subsurface geomorphology of the Pyramids Hill area on the Murrindal River (see Figure 1 for location). (a) Topographic map; (b) aerial photograph at same scale as (a); nickpoints labelled N1, N2 and N3; cross-section along line C–D on (a) shows the geology and location of the cave passage along this line

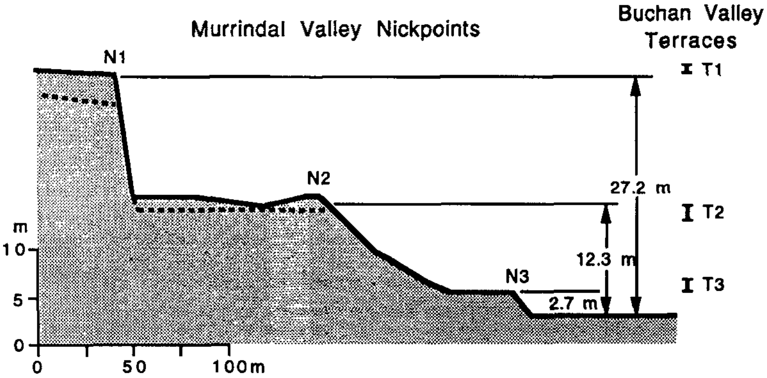

Figure 3. Long section down the Murrindal River at Pyramids Hill, showing nickpoints (labelled N1, N2 and N3) and the mean water level (dashed line) when the surface channel is active; see Figure 2 for location. Also shown are the height ranges of the river terraces in the Buchan valley (labelled T1, T2 and T3); the error bars are the result of microtopography on the terrace surfaces

Subsurface morphology

At Pyramids Hill the Murrindal River flows underground for a distance of approximately 1200 m before emerging back into the surface channel at the resurgence (Figure 2a). About 100 m of passage (Piranha Cave; M-82) leads southwards from the main sink, and represents the accessible portion of the upstream section of the cave system; it can be entered only when the sink is dry. This cave consists entirely of a narrow, tortuous passage between large collapse blocks of limestone with sharp, fretted surfaces (hence the cave name). Coarse gravel is present in the entrance section, but the grain size of the sediment progressively decreases into the cave. Only fine sands and silts occur at the limit of exploration, where a tight passage continues into rockfall.

The downstream end of the subterranean drainage system consists of about 700 m of active stream passage, with two entrances; the Dalley's Sinkhole doline (M-35) and the resurgence, Sub-Aqua Cave (M-26) (Figure 2a; Matthews, 1985). The cave system entered through Dalley's Sinkhole consists predominantly of a low-gradient passage running approximately north–south, parallel to the strike of the bedding. Collapse dominates the cave morphology, and has destroyed most of the original passage walls and roofs. Many chambers have floors covered by angular limestone boulders through which the stream flows, and the roofs are bedding planes dipping consistently westwards at 15–20° (Figure 4a). The upstream limit of the enterable passage is marked by rock fall. Some passages have retained part of their original tubular morphology, with smoothly elliptical cross-sections (Figure 4a) or gently arched roofs that cross-cut bedding (Figure 4c). The roofs of these tubular passages are consistently about 3 m above the present stream level (Figure 4a and 4c).

Approximately 10 m above the north–south section of the cave system is a higher-level passage, consisting of a series of large chambers running parallel to the stream passage below. This upper level is dominated by

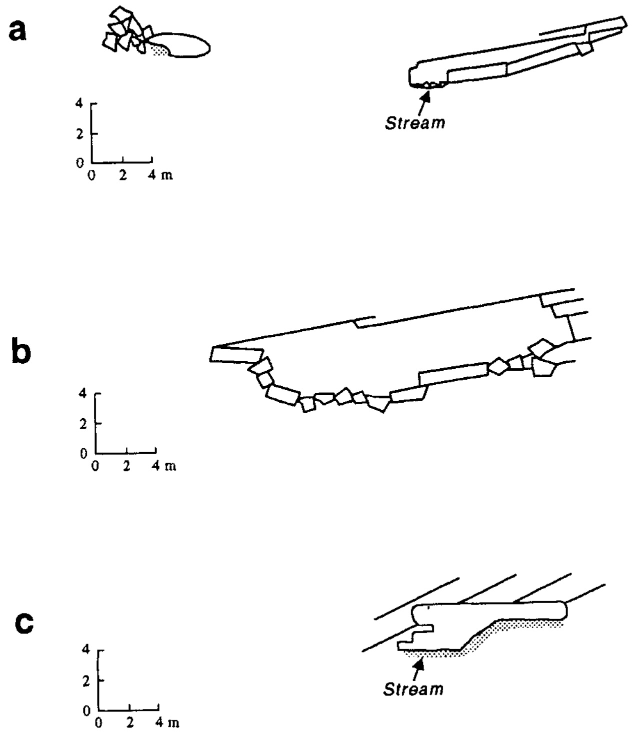

Figure 4. Three typical cave cross-sections: (a) present stream with collapse and higher abondoned passage; (b) high-level collapse passage; (c) present stream passage showing distinct phreatic development cut across the structure of the bedrock and the distribution of sediments

rockfall and has a similar morphology to the collapsed portions of the lower passage (Figure 4b). The upper chambers are highly unstable and have not been surveyed; they are not shown in the cave map in Figure 5.

The abundance of collapse material within this part of the cave system probably reflects the overwidening of the passages beyond their beam limits (Ford and Williams, 1989), as the walls are undercut by the

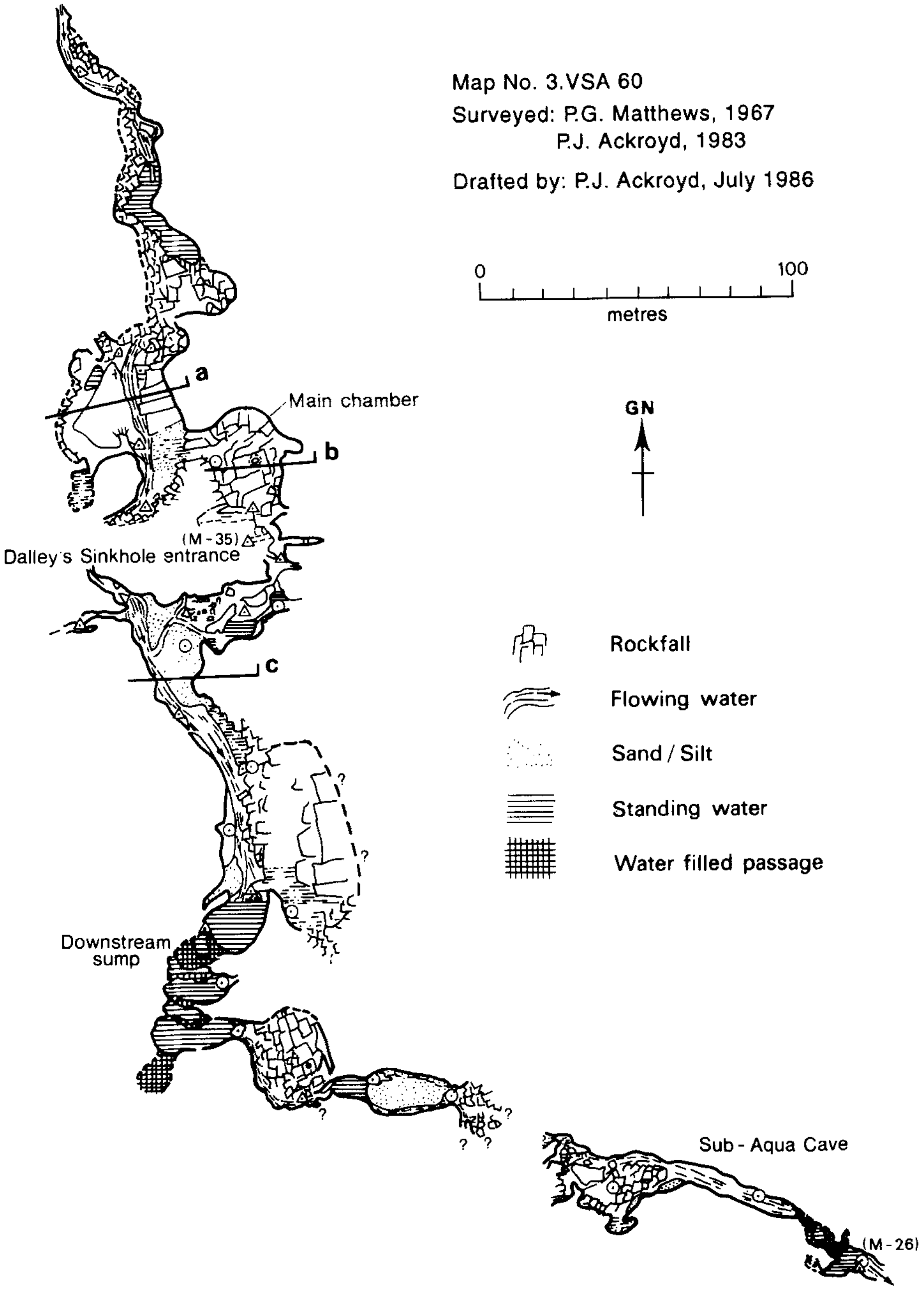

Figure 5. Map of the main accessible portions of the cave system in the Pyramids Hill. The locations of the cross sections in Figure 4 are shown

perennial stream in the cave. Structural destabilization may also be due to the increase in fissure frequency expected in a cave system of considerable age (see discussion below).

The downstream section of the Dalley's Sinkhole system has quite a different character. Firstly, it runs westnorthwest–eastsoutheast (Figure 2a), parallel to a major joint direction and more or less perpendicular to the strike of the bedding (and the upstream part of the cave). Secondly, it is characterized by water-filled sections that must be dived, separated by rockfall chambers. The water-filled passages are more or less tubular in shape, several metres wide and high, with gently arched roofs that dip up to a metre below the water level. The floors of these passages may be as much as 10 m beneath the water level.

Sediments through the Dalley's Sinkhole cave system consists of fine gravel and sand in the active channel, and silt and clay along the banks where the passages are wider. Lines of plant debris adhering to the cave walls high above the stream result from slack water deposition during floods. Thus, even during flood events on the surface, flow velocities in the cave are not fast. Rockfalls partially dam the flow of water, creating low-energy environments upstream of the constrictions, and allowing deposition of fine sediments and organic material. There are no coarse fluvial sediments in Dalley's Sinkhole cave, indicating that the pebbles and cobbles of the surface stream bedload are not transported into this part of the subsurface system. Coarse gravel is, however, present in the upstream part of the system (Piranha Cave), as mentioned above.

The stream that flows through the Dalley's Sinkhole system emerges at the Murrindal River from Sub-Aqua Cave (M-26) (Figure 2a); an impenetrable rockfall prevents connection of the two caves. The stream flows out through an elliptical passage several metres wide and high; the roof dips just below water level. After a shallow dive, a high canyon 5–6 m wide is reached. The walls rise up almost vertically and have distinct notches, and the ceiling, which is about 30 m high, reaches almost to the surface at this point, as indicated by an influx of soil (P. Matthews, personal communication). Further upstream is a large rockfall chamber, with the stream emerging through the collapsed blocks.

Overall, the Dalley's Sinkhole–Sub-Aqua system has a low gradient and lies close to base level (represented by river level at the resurgence). The northern (upstream) end of Dalley's Sinkhole cave is approximately 25 m below the level of the sink in the Murrindal River. The floor of the north–south (strike parallel) part of the cave lies at stream level; however, once the cave has changed direction and runs perpendicular to strike, the floor often descends several metres below water level.

SURFACE AND SUBSURFACE NICKPOINT DEVELOPMENT

Timing of nickpoint development

The upstream migration of a nickpoint results in relatively rapid local incision due to the sudden drop in base level, and can be expected to leave a discernible imprint on the landscape. This lowering of the channel by incision leads to the abandonment of the existing floodplain to form a paired river terrace. Thus, in any particular area there should be a correlation between nickpoints and terraces, provided both are still preserved and recognizable. However, nickpoints migrate relatively rapidly upstream, so they are often far removed from the terraces and, in addition, nickpoints may flatten out as they retreat and be effectively eliminated (Leopold *et al.*, 1964; Gardner, 1983). As a result, it is often difficult to find nickpoints corresponding to particular sets of river terraces.

In the case of the Buchan area, this correlation can be demonstrated, as the heights of the river terraces in the Buchan Valley very closely match those of the nickpoints in the Murrindal Valley at Pyramids Hill (Figure 3). The correlation shows that the nickpoints which passed through the Buchan Valley have also migrated up the Murrindal Valley. The formation of each bedrock terrace and corresponding epiphreatic cave level in the Buchan Valley required an extended period of geomorphic stability (stillstand). This means that after each of the three independent nickpoints migrated upstream, there must have been sufficient time for valley widening, floodplain formation and epiphreatic cave development (Webb *et al.*, 1992).

The timing of events that led to the formation of the terraces and epiphreatic cave levels in the Buchan Valley has been constrained to some degree using palaeomagnetic dating of cave sediments (Webb *et al.*, 1992; Downey and Webb, in press). The lowest cave level contains magnetically reversed sediments, suggesting that the last of the three stillstands responsible for the development of the cave and terrace levels predates 730 ka. Since this time, base level has only been lowered 2–3 m by fluvial incision, providing a maximum incision rate of approximately 4 m Ma^{-1}. Similar incision rates have been calculated for longer-term erosion in the Buchan area (Webb *et al.*, 1992), and for other areas in the eastern highlands of Australia (e.g. Bishop, 1985; Fried and Smith, 1992). Although rates of geomorphic change have obviously not been uniform, as shown by the presence of cave and terrace levels in the Buchan landscape, if we assume, for the sake of the argument, that the rate of incision has been more or less constant, the maximum ages of the middle and highest terraces would be about 3 Ma and 7 Ma, respectively (using the incision rate derived above and the terrace heights). Thus the time for terrace and cave formation is probably in the order of several million years. This is also suggested by the considerable extent of the terraces in the Buchan Valley and the cave levels which match them (Webb *et al.*, 1992).

The ages presented above, although they rely on the assumption of uniform process rates, are not unreasonable. Bedrock terraces extending up to 45 m above river level along the Potomac and Susquehanna Rivers, eastern U.S.A., have been ascribed ages of up to several million years (Reed, 1981; Pazzaglia and Gardner, 1993).

Nickpoint spacing within the surface channel

Because the periods of stillstand probably lasted several million years, each nickpoint in the Murrindal River would have had millions of years to migrate upstream before the next nickpoint formed. Thus, the horizontal spacing between the nickpoints should be considerable, of the order of kilometres. However, the nickpoints are only about 100 m apart (Figure 3). This discrepancy can be explained by the progressive development of subsurface drainage and its effects on the surface hydrology.

Before the first nickpoint incision, a cave system was already present bypassing the meander around Pyramids Hill; the sink and resurgence were most likely close to their present positions (Figure 2a). Probably only a small proportion of the river discharge flowed through the cave at this time, because the difference in gradient between the subsurface flow path and the surface channel was not great (about 0·012 and 0·017, respectively). However, when the first nickpoint migrating up the Murrindal River reached the south side of Pyramids Hill, it encountered the resurgence of the cave system. The 15 m of incision associated with this nickpoint would have lowered the resurgence by this amount, increasing the gradient of the cave to around 0·03, but only increasing the gradient of the surface channel to approximately 0·02; the difference between the two gradients increased from 0·005 to 0·01. Thus the subsurface system would suddenly have had a substantially steeper hydraulic gradient than the surface channel, and a greater proportion of river water would have been captured by the subsurface system. Lowering of the resurgence may also have partially straightened out some of the zigzags in the cave passages (see discussion below), enabling faster flow rates through the cave. Thus there would have been a marked drop in flow in the surface channel between the sink and resurgence, thereby slowing the retreat of the nickpoint. This sequence of events has also been noted by Warwick (1960) in British karst landscapes. Even if the entire discharge of the river at normal flow was captured by the cave, high flow events that exceeded the capacity of the subsurface conduits would still cause the nickpoint to retreat. However, the rate of retreat would be greatly decreased, because the size, frequency and duration of these flood events would have been substantially reduced by the subsurface capture. The same sequence of events happened to the subsequent two nickpoints, which caught up with the first one. Upstream movement of the nickpoints is now very slow, and they are effectively trapped in this partly abandoned section of the Murrindal River.

Morphology of surface nickpoints

As a nickpoint migrates upstream in a bedrock channel, it may either be maintained as a steep headwall, or flatten out and be eventually eliminated, depending on lithology and associated rock mechanics, as well as hydraulics of the flow (Leopold *et al.*, 1964; Gardner, 1983). The nickpoints in the Murrindal River have retained near-vertical faces (Figure 3), probably due to the pervasive, closely spaced vertical jointing in the rhyolites of the Snowy River Volcanics, which are very resistant to weathering. In addition, the flow is sufficient to transport the eroded material away from the bases of the nickpoints. A further factor may be that the nickpoints appear to propagate upstream as a result of pothole development in the drawdown reach of the nickpoint, and the subsequent breaching of the upstream walls of the potholes.

Cave development

To explain the evolution of subsurface systems, Worthington (1991,1993) proposed that there is a preferred flow path between sink and resurgence in any cave, and dissolution along this path will develop a substantial passage which acts a phreatic (water-filled) conduit. The conduit is typically smoothly elliptical in cross-section, and forms as a single large-scale phreatic loop, i.e. the cave passage descends from the sink and rises up to the resurgence. Smaller phreatic loops may be superimposed on the larger loop (see below). The maximum depth of the conduit below the water table is reached more or less midway between the sink and resurgence, and is primarily a function of aquifer length and stratal dip (Worthington,1993). Long aquifer length and steep stratal dip cause the conduit to be located deeper than if the aquifer length is limited and dips are gentle.

Below the major conduit described above there will always be a lower flow field, consisting of smaller but otherwise similar passages carrying relatively little of the overall flow though the subsurface system (Worthington (1991); this is the nothephreatic solution of Jennings (1985).

Cave systems often consist of separate components running parallel to the strike and to the dip direction of the limestone bedding. Cave passages parallel to strike can follow an individual bed or bedding plane, and may therefore develop as subhorizontal conduits in shallowly dipping strata. However, in the dip direction the cave passage has to cut across the bedding, and must utilize joints or faults to achieve an overall horizontal path (Worthington, 1991). This means that the dip parallel passage will consist of numerous small-scale phreatic loops, as the conduit alternately runs along bedding planes and then perpendicular to them, following joints. Thus a dip-parallel passage will have an overall zig-zag appearance when viewed in long section (parallel to the passage). The high points of the loops will rise to just below the water table in shallowly dipping strata, and the low points will be substantially deeper.

At Pyramids Hill the subsurface system fits this model well. The upstream strike-parallel passage is more or less horizontal, and the dip-parallel section is characterized by water-filled sections that must be dived, with roofs that dip below the water level. Where collapse has not destroyed the original walls and roofs, passages are typical of major phreatic conduits, with smoothly elliptical cross-sections or gently arched roofs that cross-cut bedding.

Because the dip of the limestone is shallow and the distance from sink to aquifer is relatively short, Worthington's (1991, 1993) model would predict that at Pyramids Hill the strike-parallel passage would develop just below the water table, whereas in the dip-parallel passage the tops of the phreatic loops would rise close to the water table. Thus the gently arched roof levels about 3 m above the floor of the strike-parallel section (Figure 4a and 4c) probably represent the major conduit that fed the resurgence when the Murrindal River was at the terrace 3 level (Figure 3). The higher-level rockfall chambers, approximately 10 m above the strike-parallel section, may be the collapsed remnants of the conduit that developed when the river lay at terrace 2 height (Figure 2a). Within the dip-parallel part of the system, the ceiling of the 30 m high canyon in Sub-Aqua Cave is most likely the crest of a phreatic loop (since incised; see below). From the height of the crest, the water table at the time it formed must have been at terrace 1 level, predating incision of any of the nickpoints (Figure 3).

Nickpoint retreat in subsurface systems

When the water table at a cave resurgence is lowered by nickpoint incision, the major conduit feeding the resurgence will be modified by nickpoint retreat through the underground system. The nickpoint may be transmitted through the cave by the abandonment of the main phreatic conduit for smaller, lower-level (nothephreatic) passages (Ford and Williams, 1989; Worthington, 1991). The steepening of the hydraulic gradient resulting from nickpoint incision will cause the nothephreatic passages to become hydraulically more efficient. They will quickly capture flow from the overlying major conduit, which will be completely abandoned if the water table drops far enough.

Alternatively, the nickpoint may be transmitted via simple downcutting within the major conduit; this is most likely if the conduit is already partly drained (i.e. vadose) and has gentle gradient (Ford and Williams, 1989). Downcutting will also diminish the vertical amplitude of phreatic loops by entrenchment of the loop crests, which can also be bypassed through flow capture by nothephreatic passages (Worthington,1991). If the water table drops to a level close to that corresponding to the bases of the phreatic loops in the original conduit, there will be major entrenchment or bypassing so that few loop bases remain, and in the final case a low-gradient river cave will result. The change from unmodified conduit with phreatic loops to subhorizontal river cave corresponds to the 'four-state model' of cave evolution proposed by Ford and Ewers (1978).

In the case of the Pyramids Hill cave system, both abandonment and entrenchment of cave passages have occurred. Within the downstream dip-parallel section, substantial downcutting of phreatic loop crests has taken place, so the roofs of the loop bases now descend only a metre or so below the present water table. The amount of entrenchment that has occurred is indicated by the height of the canyon in the resurgence cave (Sub-Aqua (M-26); Figure 5); the ceiling here rises approximately 30 m above floor. The straightness of this passage suggests that entrenchment in the dip-parallel section has been controlled by a major joint.

Within the strike-parallel part of the system, the rapid lowering of the water table resulting from the upstream migration of the surface nickpoints probably caused some entrenchment down-dip, leading to major bedding-plane collapses as the passages were widened. This may have been particularly true of the most recent nickpoint incision, where the amount of lowering was small (about 3 m; Figure 3) and probably did not exceed the vertical extent of some of the active phreatic passages. However, the lack of continuous canyons of similar height to the surface nickpoints connecting the higher- and lower-level strike-parallel conduits suggests that the nickpoints were transmitted through this section largely by abandonment rather than downcutting. Remnants of abandoned phreatic conduits (Figure 4a, and probably the high-level collapse chambers) are present in some places. Thus the nickpoints did not migrate up the subsurface channel as they did on the surface.

Nickpoint entrapment within the cave system

The drop in water level corresponding to the combined height of the three nickpoints in the surface channel is in the order of 28 m. This is fully accommodated in the inaccessible rockfall passages of the upstream portion of the cave; the height difference between the surface sink in the river bed and the water level in the upstream part of the Dalley's Sinkhole systems is also about 28 m (Figure 3). This poses an intriguing question. Why have the changes in base level not yet been transmitted to the surface channel upstream of the sink? There is no lithological reason for the nickpoints to have remained stationary, as immediately around and upstream of the sinks the river bed is cut in limestone. Although some upstream sinks have developed, these apparently take a relatively small proportion of the river flow, and there has been no appreciable lowering of the river bed around them. This is despite the fact that there has been ample time available for the nickpoints to have moved through the cave system, probably several million years (for the first nickpoint).

The answer to this question comes from a consideration of the processes of erosion occurring at the surface and underground nickpoints at Pyramids Hill. In the bedrock surface channel, flood events are the only times when significant erosion is carried out; the surface water is armed with coarse corrosive materials and mechanical erosion dominates. At the sink, the water enters the confined spaces of the collapse pile and is partially dammed. The resulting decrease in the velocity of the water flow causes the coarse bedload to be dropped. Additionally, the rockfall material acts as a sieve, trapping any coarse gravel which does get washed into the underground system. As a result, the sediments within the downstream cave are predominantly fine-grained. The screening effect of collapse piles associated with diffuse sinks is likely to be a general feature in karst terrains and may explain the lack of coarse sediments in many caves.

In the surface channel there is a mixed corrasional–corrosional erosional environment, but the lack of coarse bedload in the underground system means that the mechanical component of the erosional regime there is drastically reduced. Flow velocities through the cave are generally low, as shown by the irregularly fretted surfaces of most of the passage walls throughout the cave; regularly scalloped surfaces indicating

Table I. Median water chemistry values (in ppm) and saturation index with respect to calcite (SI_c) for the Murrindal River upstream of the sink and the resurgence at Sub-Aqua Cave (from Ellaway, 1991)

	Ca^{2+}	Mg^{2+}	HCO_3^-	SI_c
Murrindal River	20·2	8·7	76·8	−0.63
Sub-Aqua (M-26)	29·6	8·1	98·5	−0.58

higher flow velocities are rare. Thus solution is the dominant erosive agent (Newson, 1971). However, a comparison of the chemical composition of the Murrindal River with that of the water flowing out of the cave resurgence (Table 1) shows that relatively little solution is occurring within the cave, as the calcium and bicarbonate levels of the resurgence water are only slightly elevated with respect to the river. Taken together, this evidence indicates that the erosion rate in the underground channel is probably less than that on the surface.

In addition, there is a difference in the volume of material that must be removed to lower the channel. As the surface nickpoints migrate upstream, only the base and sides of the channel are eroded, along with minor contributions from the valley slopes. In the subsurface system, however, additional material derived from collapse of the ceiling needs to be removed. Therefore, to transmit a drop in base-level through the cave system requires the removal of a larger volume of rock than for the surface migration of a nickpoint.

These two factors (low erosion rates and large volumes of material to be eroded) may explain why the drops in base level within the cave system at Pyramids Hill have not yet been transmited upstream beyond the subsurface system. It is not clear if the subsurface nickpoint is effectively trapped at its present location, although this seems likely, given the time span involved. The base-level change could eventually move past the sink, either by the continued upstream migration of the surface nickpoint, or by solutional enlargement of the upstream part of the cave. In the latter case, a major blind valley would develop, so the subsurface system would be more efficient in capturing the surface discharge, and even high-flow events could be accommodated within the cave system.

CONCLUSIONS

This study has shown clearly that by linking together separate elements of the landscape, it is possible to achieve insights into the geomorphological processes acting in an area. Correlations have been made between the three nickpoints in the Murrindal Valley and the three paired bedrock terraces and epiphreatic cave levels in the Buchan Valley. This showed that terrace formation in the Buchan Valley can be attributed to the upstream migration of nickpoints; the resultant river incision caused abandonment of the erosional floodplain surfaces, and cave passages developed during times of base-level stillstand. Evidence from dating of the cave levels indicates that the first and second nickpoints are several million years old, and so the periods of stillstand were also in the order of several million years. Similar long-term persistence of nickpoints in the eastern Australian highlands has been documented by Fried and Smith (1992), and together these studies provide additional examples of the persistence of old forms in this landscape, which is characterized by long-term stability and low incision rates (e.g. Young, 1983; Bishop, 1985).

The present location of all three nickpoints at Pyramids Hill is a direct result of the development of a subsurface meander cut-off in the Buchan Caves Limestone. This led to the abandonment of the surface channel containing the nickpoints, except during periods of high discharge. The nickpoints are now less than 100 m apart, but this reflects the fact that they are now effectively stranded, rather than the period of time between the drops in base level that formed them. The subsurface drainage system has resulted in decreased flow over the nickpoints and therefore greatly reduced rates of retreat. The stranding of the nickpoints at this location means that they are well preserved and relatively close to the river terraces with which they are genetically associated; often river terraces and nickpoints are widely separated. Thus, meanders bypassed by subterranean piracy are often likely to contain well-preserved nickpoints, and may therefore give insights into the geomorphic development of an area.

The changes in base level caused by the upstream passage of the nickpoints in the Murrindal River are still located in the subsurface system, even though the time which has been available for the first nickpoint to move through the system is in the order of several million years. The extremely slow rate of retreat is related to the nature of the upstream part of the cave system. The diffuse sinks within the Murrindal River are characterized by extensive development of collapsed limestone blocks. The collapse material acts as a trap for the coarse bedload material transported by the Murrindal River, so there is an absence of coarse sediments in the caves. As a result, the mechanically dominated erosional environment in the surface channel changes to a chemically dominated one underground, causing slower rates of downcutting in the cave. In addition, to transmit a drop in base level through the cave system requires the removal of a larger volume of rock than for the surface migration of a nickpoint, because any collapse material in the subsurface system must also be removed. These factors have slowed the migration of the base-level changes through the subsurface system, and may be a general feature in caves that have diffuse sinks as their main inputs.

ACKNOWLEDGEMENTS

This research was funded by an Australian Research Council grant to B.L.F. and J.A.W., and a Rimstone grant to D.H. We wish to acknowledge the assistance of the Victorian Speleological Association Inc. and its members (particularly Peter Ackroyd and John Van Dyk) in the provision of information and data from the speleological records. Figures 1, 2 and 4 were drafted by Chandra Jayasuriya.

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