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GEOMORPHOLOGY, STRATIGRAPHY AND ^{14}C-CHRONOLOGY OF ANCIENT TUFAS AT LOUIE CREEK, NORTHWEST QUEENSLAND, AUSTRALIA

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ABSTRACT Louie Creek is a karst spring-fed stream situated in the seasonally humid tropics of northwest Queensland, Australia. It rises as a series of small exsurgences along the eastern edge of the Barkly Tableland. As it enters the lowlands of the Carpentaria plain, the creek deposits tufa which produces a series of cascades. This modern tufa extends discontinuously for about 1.5 km. A series of ancient tufas, in places lying adjacent to sites of modern deposition, extends discontinously for about 8 km downstream. At least two ancient tufa units are preserved at one location, Little Indarri site. The older unit comprises a sequence of well-preserved barrages with an orientation transverse to present-day stream flow. In places, erosion has reduced these barrages to their calcrete substrate. The older tufa is overlain in places by sediment which has become cemented to form a second calcrete unit. This sediment is in turn succeeded by the younger ancient tufa. Subsequent river incision has removed part of the sediment from the older unit and exposed several contact points between the ancient tufa and calcrete units. Radiocarbon dating of the Little Indarri site tufas, as well as other ancient Louie Creek units, yielded apparent ages ranging from ~30 to ~14 ka BP, suggesting that conditions were sufficiently wet during the period immediately preceding and throughout the Last Glacial Maximum for tufa depostion to occur. However, ancient tufa formation occurred during a phase of net river aggradation. There is geomorphic evidence that such aggradation was a result of an increased sediment supply to the fluvial system, most likely in response to conditions drier than present. Results from studies elsewhere in the region support such a Late Pleistocene trend. Incision of Louie Creek, which postdates the youngest of the dated ancient tufas, is most likely to have resulted from a shift to wetter conditions during the early Holocene.

RÉSUMÉ *Géomorphologie, stratigraphie et chronologie au ^{14}C des tufs anciens du Louie Creek, au nord-ouest du Queensland, en Australie.* Le Louie Creek est un ruisseau issue d'une source karstique dans les tropiques humides du nord-ouest du Queensland. En entrant dans la plaine de Carpentaria, le ruisseau dépose un tuf qui forme une série de cascades. Ce tuf moderne s'étend de façon discontinue sur environ 1,5 km. Une série de tufs anciens, parfois adjacents, s'étendent de façon discontinue sur environ 8 km en aval. Au moins deux unités de tuf ancien sont conservées à un endroit, le site de Little Indarri. L'unité la plus ancienne comprend une suite de barrages bien conservés dont l'orientation est transversale à l'écoulement actuel. Le tuf le plus ancien est parfois recouvert par un sédiment qui s'est cimenté pour former une deuxième unité d'encroûtement. Ce sédiment, à son tour, laisse place à un tuf ancien plus récent. L'encaissement subséquent du ruisseau a fait disparaître une partie du sédiment de l'unité plus ancienne. La datation au ^{14}C des tufs de Little Indari ainsi que d'autres unités anciennes du Louie Creek a donné des âges entre ~30 et ~14 ka BP, indiquant que le climat était suffisamment humide au cours de la période précédente et tout au long du dernier maximum glaciaire pour permettre le dépôt de tuf. Toutefois, la formation du tuf ancien s'est produite pendant une phase d'alluvionnement important. Des indications géomorphologiques montrent qu'un tel alluvionnement était le résultat de l'accroissement de l'apport sédimentaire dans le réseau, tout probablement en réponse à un climat plus sec. Les résultats d'études entreprises ailleurs dans la région corrobore cette tendance au Pléistocène supérieur. L'encaissement du Louie Creek, survenu après la formation du plus récent des tufs anciens, résulte probablement d'un changement à des conditions plus humides survenu au cours de l'Holocène inférieur.

ZUSAMMENFASSUNG *Geomorphologie, Stratigraphie und ^{14}C-Chronologie der alten Tuffe am Louie Creek, Nordwesten von Queensland, Australien.* Der Louie Creek ist ein im Frühling genährtes Karst-Flüßchen in den saisonbedingt feuchten Tropen von Nordwest-Queensland. Er entspringt als eine Serie von kleinen Ausflußstellen längs des östlichen Randes des Barkley-Tafellandes. Sobald er in die Niederungen der Carpentaria-Ebene eintritt, lagert er Tuffe ab, welche eine Serie von Wasserfällen produzieren. Dieser moderne Tuff breitet sich diskontinuierlich über etwa 1,5 km aus. Eine Serie von alten Tuffen, welche sich an Plätzen neben der modernen Ablagerung befinden, erstreckt sich diskontinuierlich über etwa 8 km flußabwärts. Mindestens zwei alte Tuff-Einheiten sind an einer Stelle erhalten, am Platz von Little Indarri. Die ältere Einheit umfaßt eine Folge von guterhaltenen Dämmen, deren Orientierung quer zum heutigen Lauf liegt. Der ältere Tuff ist an manchen Stellen von Sediment überlagert, das so verkittet ist, daß es eine zweite Verkrustungseinheit bildet. Auf dieses Sediment folgt wiederum ein alter Tuff neueren Datums. Die darauffolgende Fluß-Eindämmung hat einen Teil des Sediments der älteren Einheit ausgegraben. Radiokarbondatierung der Tuffe von Little Indarri sowie andere alte Louie Creek-Einheiten lieferten offensichtliche Alter zwischen ~30 bis ~14 ka v.u.Z. Sie lassen erkennen, daß das Klima während der Zeit unmittelbar vor und während des letzten glazialen Maximums feucht genug war, um die Ablagerung von Tuff zu ermöglichen. Indessen geschah die alte Tuff-Bildung während einer Phase reiner Flußanschwemmung. Geomorphologische Belege zeigen, daß diese Anschwemmung wegen einer verstärkten Sediment-Zufuhr zu dem Fluß-System stattfand, höchstwahrscheinlich als Reaktion auf trockenere klimatische Bedingungen als gegenwärtig. Die Eindämmung des Louie Creek, welche nach der Bildung des jüngsten der datierten alten Tuffe stattfand, ist wohl auf einen Wechsel zu feuchteren klimatischen Bedingungen während des früheren Holozäns zurückzuführen.

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INTRODUCTION

Tufa and travertine are chemical sedimentary rocks composed largely, though not entirely, of calcium carbonate ($CaCO_3$). They form within a restricted range of environments, the most common being karst and geothermal. Amidst great terminological confusion, this paper will confine itself to 'tufa', defined here as cool freshwater calcareous deposits of any age and degree of crystallinity (Pedley, 1990).

The study of tufa deposits in Australia has received only scant attention from karst and Quaternary geomorphologists (Dunkerley, 1981, 1987; Ellaway, 1991; Viles and Goudie, 1990). Despite the continent possessing a considerable area of exposed carbonate bedrock, little is known about the extent of both modern and ancient tufas. Yet, the karst areas of Australia occupy a broad latitudinal belt from the tropics of northern Queensland to the cool temperate zone of Tasmania. This has at least two significant implications. First, there is enormous potential for examining contemporary processes of tufa formation under a range of different climatic regimes. For instance, worldwide there is a relative dearth of information about contemporary tufa deposition in environments outside the temperate regions of Europe and North America. Australia contains extensive karst areas in non-temperate regions. Thus, there is scope for research contributing to a better understanding of tufa-forming processes in such regions. Secondly, given the well-documented value of tufa in palaeoenvironmental reconstruction (Preece *et al.*, 1984; Livnat and Kronfeld, 1985; Newton and Grossman, 1988; Rousseau *et al.*, 1992), the likely preservation of ancient tufas across a broad latitudinal range in Australia represents an opportunity for investigating Late Quaternary environmental change in areas where 'suitable sites' are deemed to be absent.

In the light of the above, the principal aim of this paper is to report some preliminary findings on the geomorphology, stratigraphy and chronology of ancient tufas at Louie Creek, northwest Queensland, Australia. The findings form part of a wider, ongoing project which investigates the geomorphological and hydrochemical processes of contemporary tufa formation at Louie Creek and the environmental history of the Louie Creek region using geomorphic, biological and geochemical evidence from ancient tufas.

STUDY AREA

Louie Creek is a perennial, karst spring-fed stream draining part of the eastern portion of the Barkly Tableland (Fig. 1). Its surface catchment is situated in the seasonally humid tropics (18°45'S, 138°31'E) and experiences a summer-dominant rainfall regime with a mean annual precipitation of ~450 mm. Although the median precipitation for the period April to September inclusive is zero, the rainfall pattern is highly variable. Most precipitation derives from convective thunderstorrns, but occasionally strongly monsoonal conditions penetrate from the north giving rise to summers up to three times wetter than average. The region also experiences a significant hydrological deficit: mean annual pan evaporation is ~3000 mm. Not surprisingly, the creek has ceased to flow on at least two occasions during the past 20 years.

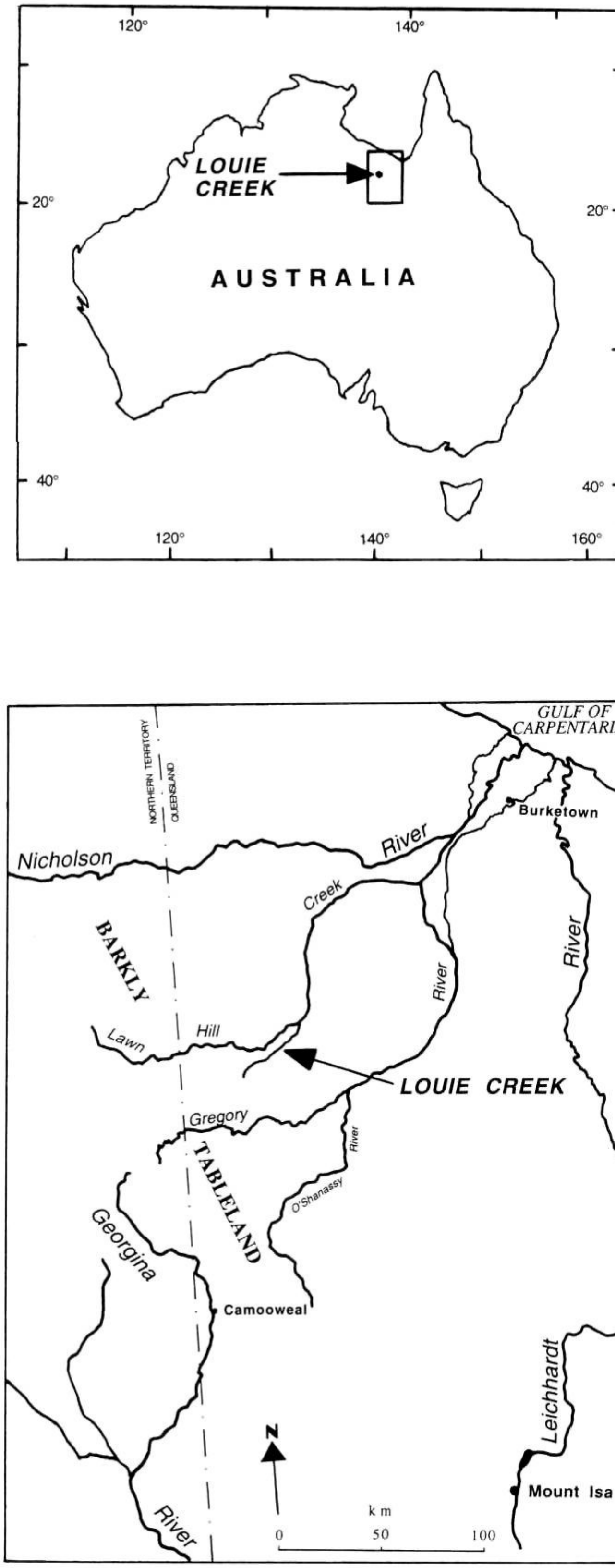


FIGURE 1. Map showing the location of the Louie Creek study area, northwest Queensland.

Carte de localisation de Louie Creek, dans le nord-ouest du Queensland.

Louie Creek rises as a series of small exsurgences adjacent to the contact between Middle Cambrian dolomite and Proterozoic sandstones and conglomerates (Sweet and Hutton, 1982). These geological units constitute the contiguous Barkly Tableland in the Louie Creek region (Fig. 2). The creek is one of a number of incised, spring-fed systems draining the Tableland, forming a series of gorges which in places exceed 50 m in depth. The creek exits the gorge terrain and flows northeast across the Carpentaria Basin, ultimately draining into the Gulf of Carpentaria. Immediately downstream of the gorge exit, the Creek deposits tufa intermittently over a distance of ~1.5 km, mostly as cascades (*sensu*

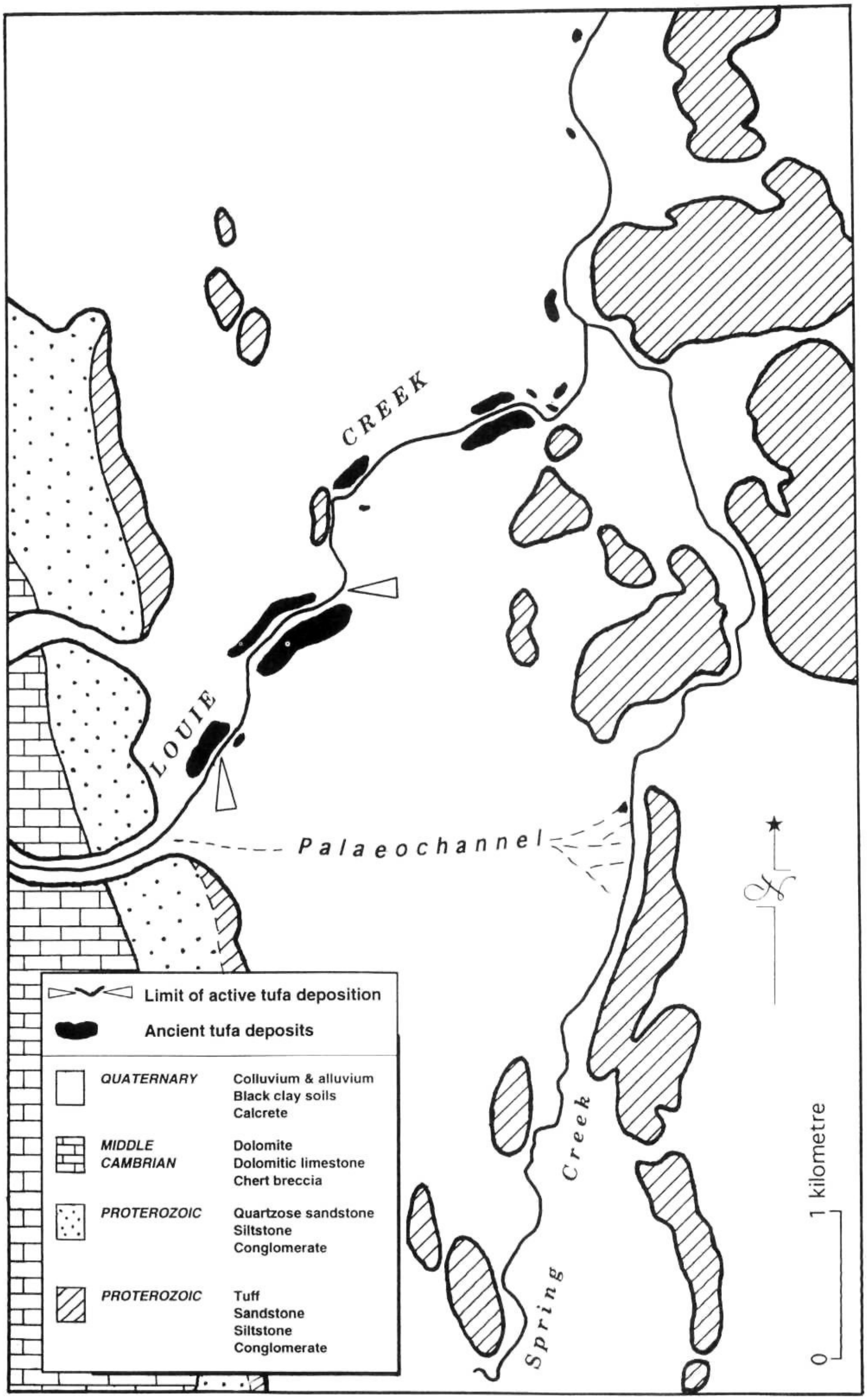


FIGURE 2. Map showing the distribution of ancient tufa deposits and the extent of modern tufa formation, Louie Creek, northwest Queensland. Note the palaeochannel, and its associated ancient tufa deposit, to the south of the present channel.

Carte de la répartition des anciens dépôts de tuf et limites de la formation actuelle de tuf, au Louie Creek, dans le nord-ouest du Queensland. Noter le paléochenal et l'ancien dépôt de tuf qui lui est associé, au sud du chenal actuel.

Pedley, 1990). In addition to the modern tufas, an extensive series of ancient tufas has been preserved (Fig. 2). These deposits both flank and underlie the modern tufas and extend downstream discontinuously for a further ~6 km.

No groundwater hydrological studies have been undertaken in the Louie Creek area specifically. However, recharge in the karst aquifers which drain to the Gulf is thought to be locally derived (G.Jacobson, Australian Geological Survey Organisation, pers. comm.).

ANCIENT TUFAS OF LOUIE CREEK

GEOMORPHOLOGY

Several ancient tufa units have been preserved at Louie Creek. They comprise unpaired terraces and partly exhumed barrage remnants. Some of the former extend for up to one hundred metres in length. Cores and river bank exposures indicate that individual units vary in thickness from less than a metre to over 3.5 metres. Textures range from dense crystalline to porous deposits to weathered, unconsolidated residuals. Tufa facies prevailing in the modern environment are evident in these ancient tufas, including phytoclastic material, and both phytoherm boundstones and framestones (*sensu* Pedley, 1990). Oncoids (Tucker and Wright, 1990) constitute the only facies at one ancient tufa site but have yet to be encountered in the modern environment. Cores through the ancient tufas reveal remains of molluscan fauna, whilst at one riverbank exposure a freshwater turtle shell was retrieved from the base of a palaeobarrage. Detailed petrological, biological and geochemical investigation of the ancient tufas is still in progress.

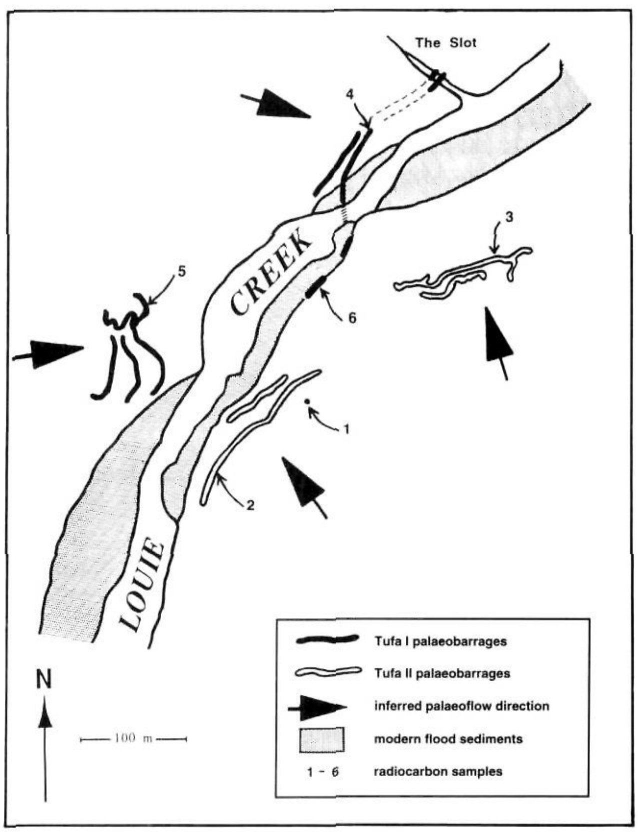


FIGURE 3. Local palaeoflow directions inferred from the orientation of ancient tufa barrages. Note the apparent palaeochannel widths, expecially those belonging to Tufa II. The map also shows the location of samples from which the Little Indarri site apparent radiocarbon ages, outlined in Figure 3a, were derived.

Directions des paléo-écoulements déterminés à partir de l'orientation des anciens barrages de tuf. Noter la largeur apparente des paléochenaux, spécialement ceux de Tufa II. La carte montre également la localisation des sites d'échantillonnage d'où émanent les âges au ^{14}C apparents (fig. 3).

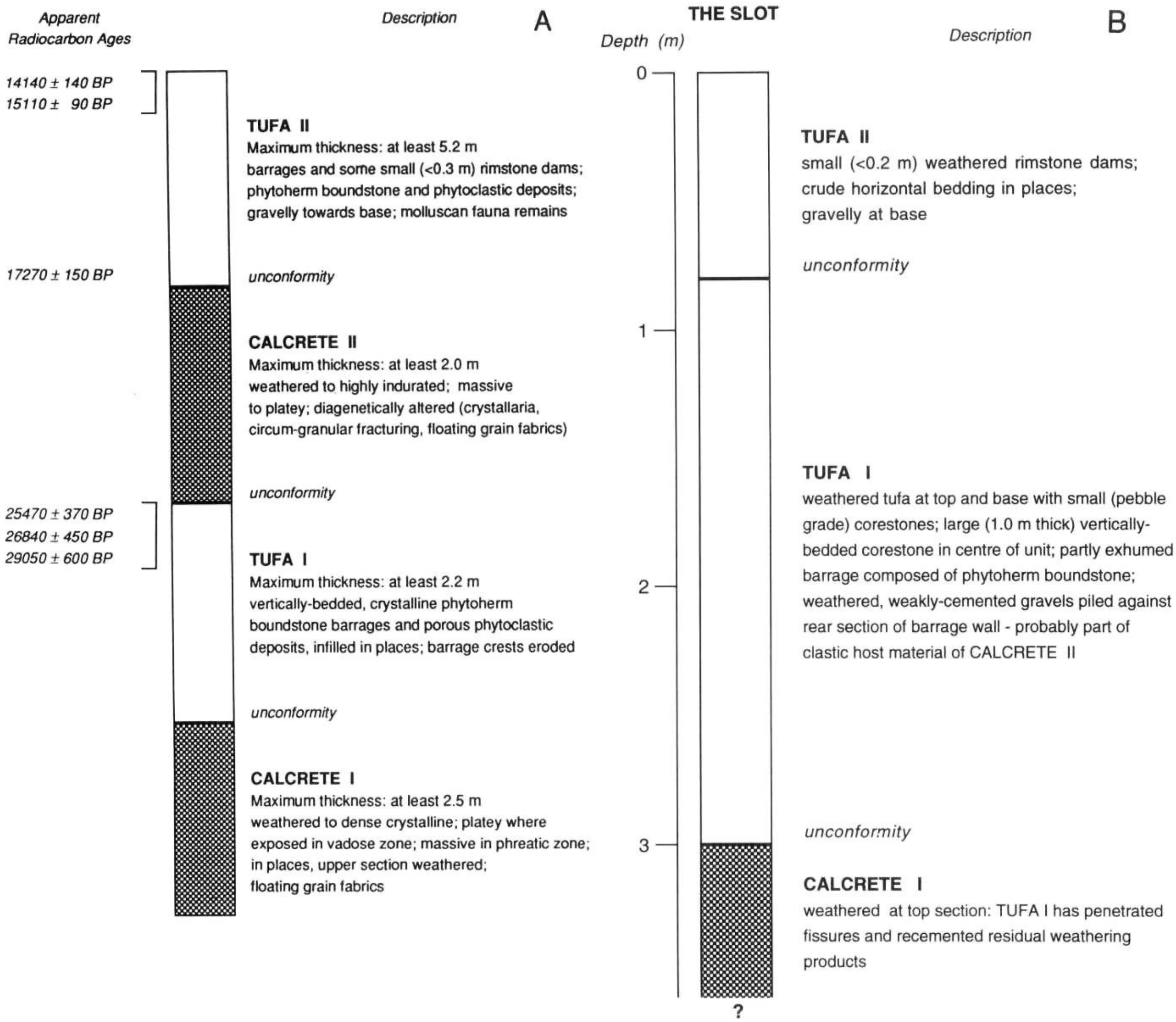
In spite of extensive weathering and erosion, it is possible to identify distinct geomorphic forms in the ancient tufas. At many sites, small (<0.3 m) rimstone dams are preserved, indicating former cascade environments. Ancient tufa barrages, defined as remnants of larger versions of rimstone dams but occupying a more significant break of slope in river long profile, are preserved at a number of sites, particularly where buried tufa has been exhumed. At some sites, these 'palaeobarrages' are oriented, allowing reconstruction of palaeoflow directions. As Figure 3 illustrates, the palaeoflows indicate significant localised shifts flow direction. The lateral dimensions of the palaeobarrages, relative to the modern channel width at sites of modern tufa formation (Fig. 3), suggest the ancient tufas were deposited under fluvial conditions quite different from today.

In places, re-entrants, notches and impact domes indicate specific sites of vertical erosion through palaeobarrage walls. Ponded sediment accumulations are also present, including formerly submerged, distinctly arcuate phytoherms. The partly exhumed tufa deposits tend to comprise vertically- to subvertically-bedded phytoherm boundstone facies, with alternating dense/porous banding indicative of microphytic growth cycles. Many individual walls have been eroded to reveal a calcrete substrate.

STRATIGRAPHY

At Louie Creek, sites preserving relationships between individual deposits are rare. River bank exposures are in many locations obscured by modern colluvial and flood deposits. Furthermore, local relief is minimal, making it difficult to correlate individual tufa terraces. In spite of this, some relatively well-preserved exposures of two individual ancient tufa units are situated at Little Indarri site, in the vicinity of modern day deposits (Fig. 2), permitting the reconstruction of a regional stratigraphy.

Four ancient units are preserved at Little Indarri site (Fig. 4a). The oldest unit is a clastic deposit which has become cemented to form a calcrete (Calcrete I). Where it is exposed above the modern water table, the Calcrete I unit is considerably weathered. A core taken through Calcrete I into the modern phreatic zone, however, reveals only minor diagenesis, mostly as crystallaria (Wright, 1990). The older of two tufa units, Tufa I, overlies Calcrete I. In places, Tufa I has penetrated fissures in the upper weathered zone of Calcrete I, re-cementing the weathering products and producing a floating grain fabric. This confirms that the $CaCO_3$-cementation of the Calcrete I host sediment preceded, and was not contemporaneous with, the deposition of Tufa I.



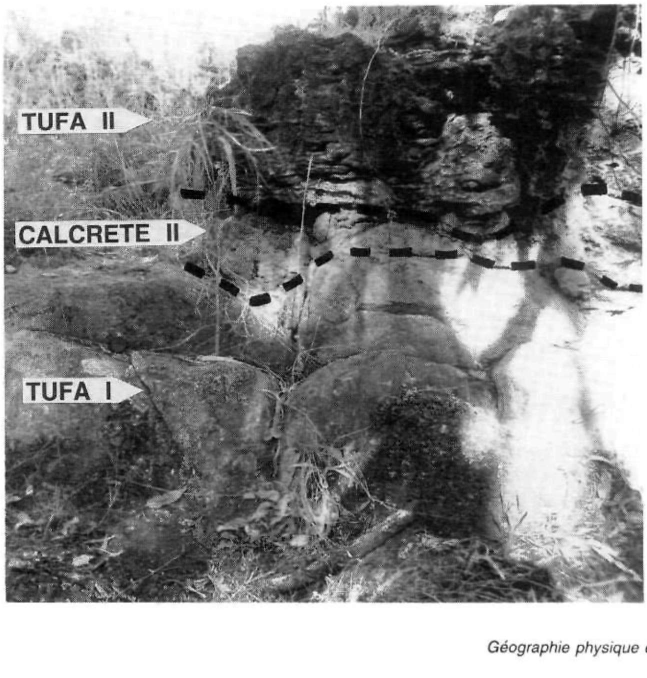


FIGURE 4. Stratigraphy of Little Indarri site, Louie Creek, northwest Queensland. A) Schematic representation of regional stratigraphy and apparent radiocarbon ages for ancient tufas. B) Typical stratigraphic section exposed at The Slot (see Fig. 3 for location). The section is ~3.5 m deep and is exposed in a narrow gully. A distinct unconformable contact is preserved between Tufa II and Tufa I. C) Stratigraphic section exposed by steam incision showing a distinct contact between Tufa I barrage and a thin band of cemented sediments comprising Calcrete II. Note the vertical bedding and planed crests of the barrage. Lens cap diameter is 5 cm.

Stratigraphie du site de Little Indarri (Louie Creek). A. Représentation schématique de la stratigraphie régionale et âges au ^{14}C apparents des anciens tufs. B) Coupe stratigraphique caractéristique à The Slot (localisation à la fig. 3). La coupe d'environ 3,5 m de profondeur apparaît dans un ravin étroit. Il y a discordance entre Tufa II et Tufa I. C) La coupe stratigraphique dégagée par encaissement du ruisseau montre un contact net entre le barrage de Tufa I et la mince bande de sédiments cimentés qui constituent Calcrete II. Noter la stratification verticale et le sommet aplani du barrage. Le bouchon d'objectif mesure 5 cm.

The Tufa I unit is exposed as partly exhumed but well-preserved palaeobarrages and as corestones in gully and riverbank sections. In the case of the former, the vertical bedding is the most striking feature and comprises alternating dense and porous banding. In bank sections (Fig. 4b), where younger overlying units prevail, the tufa is often deeply weathered, although in places the vertical bedding is still apparent in corestones, allowing them to be correlated with exhumed barrage units. At one exposure (Fig. 4c), the crests of a palaeobarrage have been planed, possibly marking a significant erosional event in the Louie Creek region and the cessation of the deposition of Tufa I. Only one exposure of Tufa I is not of the vertically-bedded, palaeobarrage type. This exposure comprises phytoclastic tufa, with well-preserved riparian vegetation casts and evidence of insect larvae activity. Some of the porespaces of this deposit have become infilled by younger $CaCO_3$-cemented sand and silt.

A second clastic unit, which subsequently also became cemented to form a calcrete (Calcrete II), unconformably overlies Tufa I. It varies in depth from a thin, almost undetectable band of <0.2 m up to >2.0 m. In places, it is massive but deeply weathered, shows evidence of considerable diagenetic alteration throughout entire vertical profiles and contains an abundance of alpha fabrics (see Wright, 1990). It is unclear whether the clastic host of Calcrete II was deposited as part of the same fluvial event which eroded the crests of the Tufa I barrage shown in Figure 4c.

The younger tufa unit (Tufa II) overlies Calcrete II. Tufa II is commonly gravelly at its base; these basal tufa-cemented gravels are distinct from the underlying cemented clastics of Calcrete II, suggesting that cementation of Calcrete II occurred prior to and not contemporaneous with the deposition of Tufa II. The greater degree of weathering in Calcrete II compared to Tufa II lends some support to this assertion.

Not all exposures preserve each of the four Little Indarri site units. For instance, at one location the Tufa I/Calcrete I sequence has been partly exhumed but no overlying younger units are preserved. In this case, the Tufa I/Calcrete I units are related to the corresponding units at other exposures on the basis of facies similarities and palaeobarrage orientation.

The modern Louie Creek occupies an incised channel. During incision, fluvial erosion has removed part of the Little Indarri site Calcrete II/Tufa II sequence to exhume the Tufa I and its underlying calcrete (Calcrete I), and has left some ancient tufa terraces perched almost 10 m above present creek level. In places, modern tufa is being formed where the creek traverses eroded remnants of Calcrete I.

The remaining ancient tufa sites located downstream of Little Indarri site (Fig. 2) bear no direct stratigraphic relationship to the regional sequence detailed in Figure 4a. In addition, further sites preserving sequences of two or more tufa units have yet to be encountered. These remaining ancient tufas (Fig. 5), cropping out as terraces and eroded palaeobar-

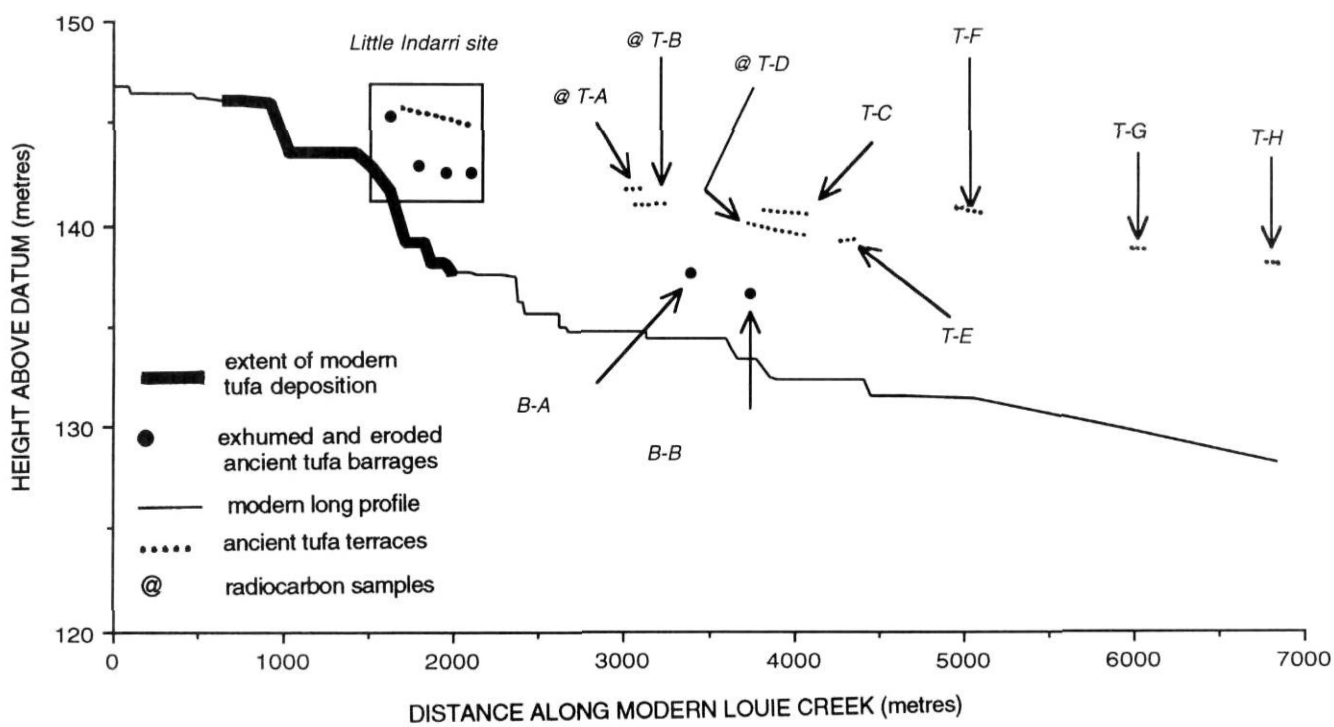


FIGURE 5. Topographic position of ancient tufa barrage and terrace deposits with respect to the modern river long profile. The heights of the ancient tufas are minima. The profile also shows the location of samples from which the apparent radiocarbon ages for the downstream terraces, outlined in Table II, were derived. Note the extent of modern tufa deposition and its confinement to the steepest reach of the creek.

Emplacement topographique de l'ancien barrage de tuf et des anciennes terrasses par rapport au profil longitudinal du cours d'eau actuel. Les hauteurs des anciens tufs sont minimales. Le profil montre aussi la localisation des sites d'échantillonnage (tabl. II) d'où émanent les âges au ^{14}C apparents. Noter l'étendue du tuf moderne limitée à la section la plus abrupte du ruisseau.

rages, share some morphological and sedimentological characteristics with the Little Indarri site tufas. For instance, the palaeobarrages are vertically-bedded and their orientation is well-preserved. A number of the terrace remnants, on the other hand, are more weathered than those at Little Indarri site and large barrage features are not preserved. At two locations, ancient tufa terraces occupy opposite banks of the modern Louie Creek, separated by only a metre of elevation (Terraces A and B, and Terraces C and D: Fig. 5). In environments of greater relief, terraces separated by one metre of elevation might be considered paired. However, the distinct differences in the degree of weathering between the terraces suggest they are not contemporaneous.

AGE RELATIONSHIPS

The problems of establishing the absolute age of tufa deposits are well documented (Srdoc *et al.*, 1986; Gascoyne and Schwarcz, 1982). Radiocarbon and uranium-thorium dating have been the two most commonly used techniques. A number of potential error sources associated with the use of both techniques can give rise to misleading age determinations, and extreme care is required in sample selection. The radiocarbon technique was chosen in this study for two reasons: to provide a preliminary estimate of the age range of the ancient tufas; and to test the stratigraphic consistency of tufa sequences at Little Indarri site.

Two significant error sources are associated with the ^{14}C dating of tufas. The first, the so-called hard water effect, occurs when 'dead' carbon from ancient bedrock dilutes the ^{14}C activity, producing dates that are anomalously too old (Williams and Polach, 1971; Bradley, 1985). Such errors are especially problematic in establishing Holocene chronologies. The second, and potentially more critical source of error, is that concerned with the contamination of tufas by younger carbonate, thus causing an underestimation of true age (Geyh and Schleicher, 1990).

It is not possible to completely solve the hard water effect problem. Estimates using bedrock dilution factors or initial activities have been used in previous studies (*e.g.* Srdoc *et al.*, 1983), but such estimates can mask significant variations and tend to be site- or stream reach-specific (Pentecost *et al.*, 1990). Ideally, non-tufaceous material (*e.g.* wood, bone, charcoal) entombed in tufa can provide a useful means for correcting dates obtained on contemporaneous ancient deposits. However, such material is not always preserved, especially in strongly oxidising environments like Louie Creek. An indication of the potential hard water effect in ancient samples can be achieved by systematic dating of modern tufas, which at the very least provides an idea of the magnitude and variation of the contemporary hard water effect and alerts the researcher to the possible range of errors likely to arise from dating ancient tufa samples. Radiocarbon dating of the inorganic fraction of two modern tufas from Louie Creek yielded apparent ages of ~1.8 and ~1.9 ka BP (Table I). A determination on the organic fraction of one of the modern tufas yielded an age of 210 ± 190 years BP (Table I), confirming it as 'modern'. Further determinations of modern tufa, as well as those of spring water, are in progress.

TABLEAU I

Apparent radiocarbon ages of modern tufas, Louie Creek, northwest Queensland

Sample type	Sample location	Laboratory code	Apparent age (year BP)
Modern tufa	modern Louie Creek	ANU-8373A	1940 ± 60
Organic residue	modern Louie Creek	*ANU-8373B	210 ± 190
Modern tufa	modern Louie Creek	ANU-8867	1790 ± 70

* Organic fraction from ANU-8373A

The second problem can in part be overcome by sampling apparently unaltered material. Facies most likely to meet closed system conditions are those from the densely laminated phytoherm boundstones (Pedley, 1990), which are fortuitously common among both ancient and modern tufas at Louie Creek. Although modern phytoherm deposits show some initial porosity, infilling of pores probably occurs during subsequent phytoherm growth; this results in the development of quite dense facies with apparent penecontemporaneous secondary carbonate infilling. Phytoherm boundstone from preserved barrage crests of the Tufa II unit, considered to be contamination-free by virtue of their topographically elevated position (*i.e., they are unlikely to have been overlain* and possibly contaminated by significantly younger carbonate), is inherently dense in places. This suggests primary development of dense facies. Samples of Tufa I would be the most vulnerable to contamination given their burial in places by younger units (*i.e.*, Tufa II, Calcrete II and younger alluvium). Although appropriate Tufa I material was sampled for dating, ages derived from such material should be treated with extra caution.

The apparent ages of ancient tufa units at Little Indarri site are shown in Figure 4a and Table II. The location of dated samples is shown in Figure 3. The ages are not only stratigraphically consistent, but form two relatively distinct clusters.

Tufa I samples obtained from three different sites yielded apparent ages ranging from ~25.5 to ~29.1 ka BP. No age was obtained of tufa from the uppermost sections of Tufa I exposures due to a lack of suitable material for dating. It is possible therefore that deposition of Tufa I may have continued for up to several thousand years after 25.5 ka BP.

The base of the Tufa II unit overlying the Calcrete II was situated at a depth of ~5.2 m in a ~7.0 m core; a sample taken at ~5.1 m yielded an apparent age of ~17.3 ka BP. A cored sample retrieved from the wall of a ~0.6 m high Tufa II palaeobarrage located adjacent to the abovementioned *core yielded an apparent age of ~15.1 ka BP, whilst a tufa* sampled from a neighbouring palaeobarrage was dated at ~14.1 ka BP. There is thus a considerable degree of internal stratigraphic consistency between the Tufa II units.

Apparent ages obtained from tufa sampled at three sites downstream of Little Indarri site (Terraces A, B and D) are highlighted in Figure 5 and Table II. Terrace A, dated at ~30.4 ka BP, is situated opposite but ~1 m higher topographically than Terrace B. The apparent age of the latter is

TABLE II

Apparent radiocarbon ages for ancient tufas and calcrete from Louie Creek, northwest Queensland

Lithology	Sample location	Laboratory code	Apparent age (Year BP)
	Little Indarri Site		
Ancient tufa:TUFA II	1. Reed Site: Core 1-3	ANU-8718	17 270 ± 150
Ancient tufa:TUFA II	2. Reed Site: Core 1-6	ANU-8713	15 110 ± 90
Ancient tufa:TUFA II	3. Reed Site: Core 1-10A	ANU-8711	14 140 ± 120
Ancient tufa:TUFA I	4. The Slot: Core 3-1A	ANU-8709	25 470 ± 370
Ancient tufa:TUFA I	5. Little Indarri: Core 1-2	ANU-8708	29 050 ± 600
Ancient tufa:TUFA I	6. Barry's Site: Core 4-2B	ANU-8707	26 840 ± 450
	Downstream terraces		
Ancient tufa	Terrace A: Core 5-3	ANU-8710	18 830 ± 160
Ancient tufa	Terrace B: surface sample	ANU-8714	30 280 ± 730
Ancient tufa	Terrace D: Core 7-1	ANU-8712	22 770 ± 270
	Palaeo-Louie Creek		
Marl/calcrete	Flood out: surface sample	ANU-8705	21 580 ± 260
Ancient tufa	Louie Ck palaeochannel: surface sample	ANU-8719	20 280 ± 210
Ancient tufa	Louis Ck palaeochannel: surface sample	ANU-8720	25 400 ± 390

N.B. Sampling locations for Little Indarri site, downstream terrace, and palaeo-Louie Creek tufas and calcrete are shown in Figures 4, 5 and 6 respectively.

~ 18.8 ka BP. This highlights the earlier point regarding non-contemporaneous terrace formation: small ~ 1.0 m differences in elevation in a landscape of low relief, such as that at Louie Creek, can represent depositional events of considerable age difference. The greater degree of weathering evident at the higher (older) exposure supports the chronological data.

The apparent ages of several ancient tufa units are yet to be determined. These include the tufa Terraces C and E in Figure 5. Terrace C, situated opposite but topographically higher than Terrace D, is more deeply weathered than Terrace D and is thus assumed to be older. The partly exhumed sets of remnant palaeobarrages (labelled B-A and B-B in Fig. 5) are morphologically and texturally identical to the Tufa I exposures at Little Indarri site and, in the absence of any ^{14}C determinations (forthcoming), are possibly contemporaneous with Tufa I.

Despite the problems associated with ^{14}C dating of tufas, the dates appear reasonably robust. Even if we increase our hard water effect to four or five thousand years, the dates suggest a phase of tufa deposition immediately prior to and throughout the Last Glacial Maximum. Further age determinations using uranium-series methods are in progress, the results of which should provide a more 'absolute' control on the ^{14}C chronology reported here.

PALAEOENVIRONMENTAL INTERPRETATION

The stratigraphic and chronological evidence from Little Indarri site suggest two episodes of tufa formation, with apparent ages ranging from ~ 29.1 to ~ 25.5 ka BP and ~ 17.3 to ~ 14.1 ka BP. Age data from ancient tufas downstream of Little Indarri site suggest that tufa formation continued during the period between Tufa I and Tufa II phases. Thus, the range of ^{14}C determinations suggests that from ~ 30 ka BP (at the latest) to approximately the start of the Holocene the climate was sufficiently wet for tufa formation to take place. However, it is worthwhile speculating in more detail on the environmental conditions during this period.

As Figure 5 demonstrates, and as discussed earlier, the modern Louie Creek is an incised channel. At some time following the cessation of Tufa II deposition, the Creek began to vertically erode through its own sediments, possibly in response to a change in hydrological conditions. Therefore, the ancient tufas were laid down under net *aggrading* conditions. The topographic position and chronology of individual ancient tufa units (Fig. 5) suggest further that some degree of scour and fill prevailed. This is not unusual in regimes of tufa deposition and is thought to be attributed to natural cycles of tufa barrage accumulation and destruction (Golubic, 1969). Therefore, it is the aspect of net aggradation which needs to be examined further.

Aggrading river profiles can result from a number of climatic, tectonic and human-induced effects. Given the tectonic stability of the region and the absence of any significant human activity (*e.g.* land clearance) in the Louie Creek catchment, the most probable explanation in this instance is a climate-driven change. Whilst rises in sea level can result in aggrading profiles, regional changes in hydrology and sediment input characteristics might also produce similar results, irrespective of global influences. A most likely explanation for this net aggrading phase is an increase in sediment input resulting from a reduced vegetation cover stimulated by a climate somewhat *drier* than present. Moisture is the major vegetation control in the region today. A reduced or more erratic rainfall, or a contraction of the wet season, would have contributed to a more sparse vegetation cover. This in turn would have increased the vulnerability of sediments to erosion and increased sediment transport into the fluvial system.

There is geomorphic evidence in the Louie Creek region supporting the claim for greater sediment input stemming from drier conditions immediately prior to and during the Last Glacial Maximum. First, sediments flanking the present stream, but intimately related to the ancient tufas, are braided and distributary in plan (Fig. 6), and show evidence of floodout events typical of high sediment yield, arid or semi-arid environments. Second, along some of these sediment-trains and floodouts are found marly calcretes, possibly derived from the drying out of shallow, $CaCO_3$-supersaturated water bodies. These calcretes are low in insoluble residue content and are distinct from those comprising Calcrete I and Calcrete II units at Little Indarri site and other calcretes underlying ancient tufas further downstream. A ^{14}C determination of one of these marly calcretes yielded an apparent age of ~22 ka (Table II, and Fig. 6), which falls within the time bracket under consideration here. Third, a large palaeochannel immediately south of the point at which Louie Creek exits the uplands (Fig. 6) once diverted flow to neighbouring Spring Creek. Radiocarbon dates of two tufas from this palaeochannel yielded ages of ~20 ka and ~25 ka BP (Table II, and Fig. 6), again within the period under consideration. The presence of an alluvial fan at the distal extreme of this palaeochannel suggests arid zone conditions characterised by a fluvial regime incapable of moving its own sediment through the system, *i.e.* net deposition. Similar ancient fan-type depositional features are found to the north where neighbouring creeks exit the Barkly escarpment, although in these instances they are not associated with a distinct palaeochannel.

A WIDER CONTEXT

Results from a number of previous studies in northern Australia also suggest drier conditions immediately prior to and during the Last Glacial Maximum. The most extensive of these studies were those carried out in the Gulf of Carpentaria (Torgersen *et al.*, 1983; De Deckker *et al.*, 1988; Jones and Torgersen, 1988; Torgersen *et al.*, 1988; De Deckker *et al.*, 1991). Data obtained from analyses of cores retrieved from the Late Pleistocene Lake Carpentaria suggest conditions in the lake catchment between ~26 ka and ~12 ka BP were drier, characterised by a fresh to brackish, lake draining an area experiencing a cyclical wet/dry, possibly seasonal, climate (Torgersen *et al.*, 1988). In other words, conditions in the Lake Carpentaria catchment appear to have been similar to but drier than today. Tentative evidence from Lake Woods, Northern Territory, and Lake Gregory, northern Western Australia, also suggests drier conditions during the time frame under consideration here (Bowler, 1981b; Bowler and Wasson, 1984), with a dune-building episode post-dating a mega-lake phase. The latter lacustral phase was thought to have ended prior to 28 ka BP (Bowler, 1981a). A similar trend from wetter to drier conditions during the same period was reported by Hughes (1981) from the Colless Creek archaeological site, less than 10 km northwest of Louie Creek.

Thus, there is some regional evidence, particularly from the Gulf of Carpentaria, that conditions during the period encompassed by the chronology of ancient tufas at Louie Creek were somewhat drier than present. One significant anomaly remains unanswered: why is modern tufa deposition now confined to such a restricted river longitudinal range, whilst ancient deposition occurred over a much greater range? There are several possible explanations, including:

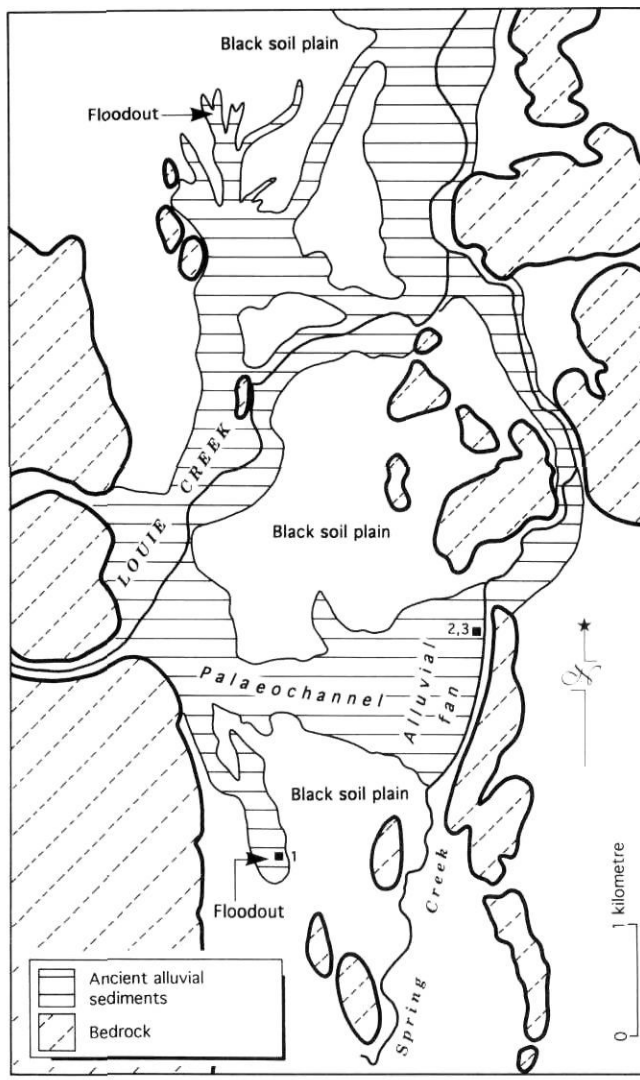


FIGURE 6. Map showing the extent and location of floodout deposits, palaeochannels, alluvial fan and braided network associated with the Late Pleistocene Louie Creek. Compared to the modern fluvial system, conditions under which these ancient sediments were deposited are indicative of high sediment inputs and low stream energy. The numbers represent sites from which samples were obtained for radiocarbon dating: 1) ancient calcrete; 2,3) ancient tufa (Tabl. II).

Carte montrant l'étendue des dépôts de crue, les paléochenaux, du cône alluvial et du réseau anastomosé associés au Louie Creek du Pléistocène supérieur. Par rapport aux conditions actuelles de mise en place des sédiments, il semble qu'il y ait eu alors un fort apport de sédiments et une faible capacité de transport du ruisseau. Les chiffres représentent les sites d'échantillonnage pour la datation au radiocarbone. 1) ancien encroûtement calcaire; 2,3) Ancien tuf (tabl. II).

(a) a relatively lower stream gradient is likely to have reduced the rate of CO_2 removal from solution, thus extending the downstream distance for waters to reach a sufficient level of supersaturation to enable $CaCO_3$ precipitation to occur;

(b) a more ephemeral Late Pleistocene Louie Creek, characterised by net sediment deposition, would have been more responsive to high magnitude events, possibly resulting in greater lateral channel migration and bedform modification, redirection of flows, and periodic relocation of turbulent sites (and thus sites of tufa deposition) in either upstream or downstream direction. Some lateral and longitudinal shifting of turbulent zones has occurred within the modern confined system since river incision. A less confined regime would perhaps have been characterised by greater channel modification and thus relocation of tufa forming sites. Further, it should be borne in mind that the areal extent of the ancient tufas does not automatically imply that all sites were active at any one time; and

(c) climatic change may have altered hydrochemistry. A reduced rainfall and/or contraction of the wet season is likely to have affected surface and karst hydrology, giving rise to, for example, greater variation in residence time of percolation waters; lower input of biogenic CO_2 owing to a reduced vegetation cover and shorter growing season in the catchment; increased runoff across less vegetated surfaces leading to a diluting stream waters. Such changes may have resulted in greater hydrochemical variations in karst water and thus spatial variations in the evolution of supersaturated solutions.

In addition, tufa deposits post-dating the Tufa II unit ($<\sim$10-14 ka BP) were probably removed during incision and headward retreat of Louie Creek. This is the most likely explanation for the absence of early to middle Holocene ages in the ancient tufa chronology presented here.

CONCLUSIONS

There is evidence from the ancient tufas at Louie Creek that tufa formation occurred up to and throughout the Last Glacial Maximum, although whether deposition was continuous or episodic is unclear. Given that the modern creek experiences periodic drying, it is likely that under the drier conditions postulated here to have occurred during the Last Glacial Maximum, the creek was more ephemeral. Although evidence from studies elsewhere in the region point to relatively dry conditions during this time, the region was sufficiently moist for tufa formation. Indeed, the presence of molluscan and other aquatic faunal remains certainly raises questions about the magnitude of climatic change. Nevertheless, the shift to a relatively drier climate appears to have triggered an increased sediment supply to the fluvial regime, giving rise to a relatively aggrading profile, possibly characterised by regular lateral and longitudinal shifting of tufa deposition sites. Incision is most likely to have resulted from the onset of a wetter phase, possibly marking the shift to interglacial conditions at the start of the Holocene. This contributed to a change to more perennial fluvial conditions and the construction of an incised, relatively stable base flow channel. Further chronological evidence is required to verify this particular claim. Evidence from the Gulf of Carpentaria, however, also suggests a return to wetter conditions in postglacial times preceding the return to fully marine conditions (Torgersen *et al.*, 1988).

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