Science Through Time: Understanding the Archive at Rennix Gap Bog, a Sub-alpine Peatland in Kosciuszko National Park, New South Wales, Australia

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Rennix Gap Bog is a sub-alpine topogenic peatland that contains up to 2 m of organic-rich sediments that have built up over the last approximately 12,000 years. This paper summarises the research and teaching activities that have been undertaken at the site, which has included consideration of the sediment stratigraphy, radiometric dating, palynology, charcoal analyses, dendrochronology and recently, the testate amoebae community composition has been documented. Much of this work is unpublished but has relevance for any future research and provides a long-term context for many contemporary environmental issues, including for issues of relevance to the management of fire in this landscape and vegetation more broadly. In the contemporary environment, the surface of the bog is vegetated with a complex mosaic of *Carex* fen, sub-alpine *Sphagnum* shrub bog and *Poa costiniana* tussock grassland. Pollen analysis suggests that this vegetation has been relatively stable for 10,000 years and prior to that the site was surrounded by sparse vegetation, similar to the alpine herb-grass community of contemporary higher altitude ecosystems. Charcoal analyses suggest that fire activity has varied through time but increased significantly in the historic period. Rennix Gap Bog has not only attracted considerable research but has also been an invaluable, accessible, site for field-based teaching and learning.

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INTRODUCTION

Understanding the role of time in the development or dynamics of plant communities augments contemporary and historical ecological information (e.g. measurements, documents, images) and allows investigation of longer processes such as climate variability, fire, species change and nutrient release. The use of natural archives is particularly relevant in Australia given the very short period of written history and lack of ecological understanding of the dynamics of most species assemblages (Clark 1990). Peatlands or ‘mires’ are organic deposits where the remains of plants have built up (with other inclusions of palaeoenvironmental significance) to provide a sequence through time which can be readily dated (Whinam and Hope 2005).

The history of peat formation in the subalpine and alpine zones of Kosciuszko National Park (KNP) has been summarized by Hope and Nanson (2015). This built on landmark studies of snow patch and lower altitude peats by Costin (1972) and Martin (1986b; 1999) together with later work, e.g. Marx et al. (2012). In these valley peatlands organic deposits have an average depth of about 80 cm but reach more than 200 cm in places (Hope et al 2012). Radiometric dating, chiefly radiocarbon (^{14}C) dating, indicate peat initiation by about 16,000 years ago at selected sites but in many cases this occurs later. Studies utilising sediments accumulating in the alpine lakes, including at Blue Lake and Club Lake (Raine 1974, Martin 1986a,b) show that the lakes were ice-free by about 15,000 years ago but only became highly organic in the last 10 or 11,000 years. Most of the sites studied to date are from high rainfall alpine sites and less is known of the subalpine environments in the rain shadow to the east of the main range.

One such archive, Rennix Gap Bog, is a subalpine peatland set in grassy woodlands on the eastern edge of KNP. This peatland has been studied for over fifty years and has been a major resource for teaching of university students. This research has resulted in considerable undocumented information regarding the long environmental history of this site. This paper summarises the scientific studies and the range of educational training carried out on the Rennix Gap Bog peatland.

Location and Site Characteristics of Rennix Gap Bog

Rennix Gap Bog has formed in the centre of one the most easterly of the open, grassed valleys on the undulating high plateau of Mt Kosciuszko. The peatland is crossed by the Kosciuszko Road as it climbs to Rennix Gap with the main part of the peatland south of the road at an altitude of 1575 m. The site is centred on 36°22.0'S 148°30.2'E and is situated within a catchment of 210 ha that has a maximum altitude of 1680 m. The valley is relatively steep and wooded along the western margin and is more open and gentle to the east. The area is underlain by Devonian granodiorite with scattered exposed tors. A small stream traverses the bog, incised about 30 cm into the peat, gradually becoming more entrenched as it flows north and then east as a tributary of Sawpit Creek.

The vegetation of highland regions tends to be strongly altitudinally zoned and the south-eastern highlands are no exception (Costin 1954, 1970; Martin 1986a). Williams and Costin (1994) noted that the distribution of vegetation in high mountain regions is primarily related to summer temperatures. In the Snowy Mountains Galloway (1965) placed the treeline at 1880 m, coinciding with the 10°C mean temperature for the warmest month. Above this treeline, a *Poa caespitosa-Celmisia asteliifolia* alliance (Martin 1986a) characterizes the alpine zone. Below this treeline, the sub-alpine zone extends from about 1830 m to about 1500 m asl.

Rennix Gap Bog occurs within this sub-alpine zone. It is an open area, of about 45 ha, surrounded by an inverted treeline of pure *Eucalyptus pauciflora* woodland. Inverted tree lines, like this one, are associated with localised physiography influencing cold air drainage (Moore and Williams 1976) and are colloquially known as 'frost hollows'. The surrounding Snow Gum woodland is near its lower altitudinal boundary at Rennix Gap Bog, with a mixed Mountain Gum (*E. dalrympleana)* – Snow Gum forest occurring about 80 m lower in altitude.

Rennix Gap Bog is vegetated with a mosaic of *Carex* fen and sub-alpine *Sphagnum* shrub bog with areas of *Poa costiniana tussock* grassland (McDougall and Walsh 2007, Hope et al. 2012). In the Kosciuszko highlands climate is influenced at a local scale by altitude, aspect and exposure, and while altitude is the dominant control, wind is an important ecological determinant (Costin 1954). In sheltered conditions at the foot of the slope on the western margin of the Rennix Gap Bog plain there are small areas of 1.5 m high thickets of *Baeckea gunniana* and *Callistemon pityoides* thickets over well-developed *Sphagnum* bog. Relatively low altitude occurrences of *Astelia alpina* and *Chionogentianis muelleriana* are also found on the bog. The western portion of the bog is somewhat sheltered by woodland and slopes but the eastern side is exposed to strong winds. The precipitation, estimated to be 1390 mm p.a., has low seasonality and includes snow-lie of about two months. The valley floor experiences severe winter frosts although the mean annual air temperature is 6.2°C.

Human History

Archaeological information from mainland Australian high altitudes is relatively scarce and most evidence of prehistoric people is relatively short (Kamminga 1995). This relates to the geological setting, which only rarely produces rock shelters (Flood 1980) and has given rise to acidic soils and sediments resulting in generally poor preservation of any material culture (Kamminga, 1995). Flood (1980 p. 1) noted, however, "several stone axes found on the peaks of the Snowy Mountains bear mute testimony to at least occasional visits by Aborigines". The oldest dated record of human occupation is only *ca.* 11,000 calibrated years before present (cal yr BP), from a cave at 1100 m at Yarrangobilly (Aplin et al. 2010). A recent archaeological survey of rockshelters around 1000-1200 m in the ACT obtained records back to 9000 cal yr BP (Theden Ringl 2016a; b).

Figure 1. The location of Rennix Gap Bog in Kosciuszko National Park. The box surrounding Rennix Gap Bog ("Boggy Plain") shows the extent of Figure 2.

Aborigines who spoke the Ngarigo language inhabited most of the Snowy Mountains and the surrounding uplands, to the north and south for a distance of about 200 km and eastwards for about 120 km from Mt Kosciusko, which was on the western boundary of Ngarigo territory (Tindale 1974). In late spring-early summer the Ngarigo were joined by a significant influx of people from surrounding areas (Sullivan 1978; Flood 1980; Kamminga 1995) associated with the collection of the Bogong moth, *Agrotis infusa*, which aestivates in vast numbers in summer amongst the granite outcrops of the high country (Keaney 2016). Larger campsites, located in valleys such as those around Jindabyne (Fig. 1), were used as staging posts or for inter-tribal trading, rites and ceremonies (Flood 1980). Smaller groups are thought to have spread out into the higher country to collect moths (Payten 1949, cited in Flood 1980; Kamminga 1995). Argue (1995) hence described a range of occupation by Aboriginal people in lower altitude valleys and itinerant camps on the higher plateaux.

Within 50 years of the first white settlement the local Aboriginal populations of the Monaro had been devastated by both smallpox epidemics and violence by Europeans (Hancock 1972, Kamminga 1995). Aborigines continued to exploit the resources of the mountains during the first half of the Nineteenth Century, but by the 1870s there were only a few remaining Ngarigo speakers living on farms and settlements in the Southern Tablelands of NSW.

The European history of the Monaro Plains dates from 1823 (Wakefield, 1969) with extensive grazing occurring by 1836 (Renshaw, 1981). Although it is commonly assumed that pastoralists used the Highlands for summer grazing and drought relief from about the mid-1860s, the Rennix Gap Bog peatland, also known as Boggy Plain, was grazed heavily after 1835 as it was one of the first open areas encountered on ascending the mountain.

Grazing of the high country continued without regulation until 1888 when limited control was established with the *Snow Lease Tenure Act* 1888 and *Crown Lands (Amendment Act)* 1889 (Hancock 1972, Good 1982). From 1890, leases were delineated and not long after, Helms (1893) was the first to 'officially' report on the extensive use of fire by pastoralists in the alpine ecosystems. Helms also expressed considerable concern at the practice.

The original Summit track, followed by a road, passed along the eastern side of Rennix Gap Bog with Harveys Camp located adjacent to the peatland. Fence lines mark this road and in places these are now (2018) nearly buried by peat. A hut is shown at the southern end of the plain in a small Crown Reserve gazetted in 1892 (Scott 2011). Rennix Gap is named after William Edward Rennix, an engineer and surveyor, who was in charge of the survey of the Kosciuszko road built between 1906 and 1909. He died of pneumonia in 1909 after being caught in a blizzard at the gap (Stone 2012). An alternative road passed west of the bog, branching from the 1909 main road, which skirted the northern side of the peatland (Fig. 2).

In 1906 the NSW State Government declared 258 km^2 around the Koscuiszko summit as the Snowy Mountains National Chase (Lembit 2002). The Kosciuszko State Park was created in 1944, covering 500 000 ha (Lembit 2002) and this resulted in further restrictions on grazing and the use of fire (Newman 1954). The present road was constructed across the swamp, presumably post-WWII, and "improved" with drainage on the upstream side. Grazing ceased in 1952 but has continued at a low level due to feral stock, deer and more recently horses. Kosciuszko National Park (KNP) was formally gazetted in 1967 and the first management plan was approved in 1974 (Lembit 2002).

Scientific Research and Teaching at Rennix Gap Bog

On the advice of Alec Costin, who had studied the region as part of his monograph *A study of the ecosystems of the Monaro Region of New South Wales* (Costin 1954), Rennix Gap Bog (as "Boggy Plain") was investigated by Tony Martin (University of Sydney) from 1959 onwards. Martin (unpublished, Figure 3) made a comprehensive vegetation map and described the stratigraphy of the sediments on site from on three sediment cores, which were located relatively close to the main road, and 10 radiocarbon (^{14}C) dates. Martin also worked on the fossil pollen of

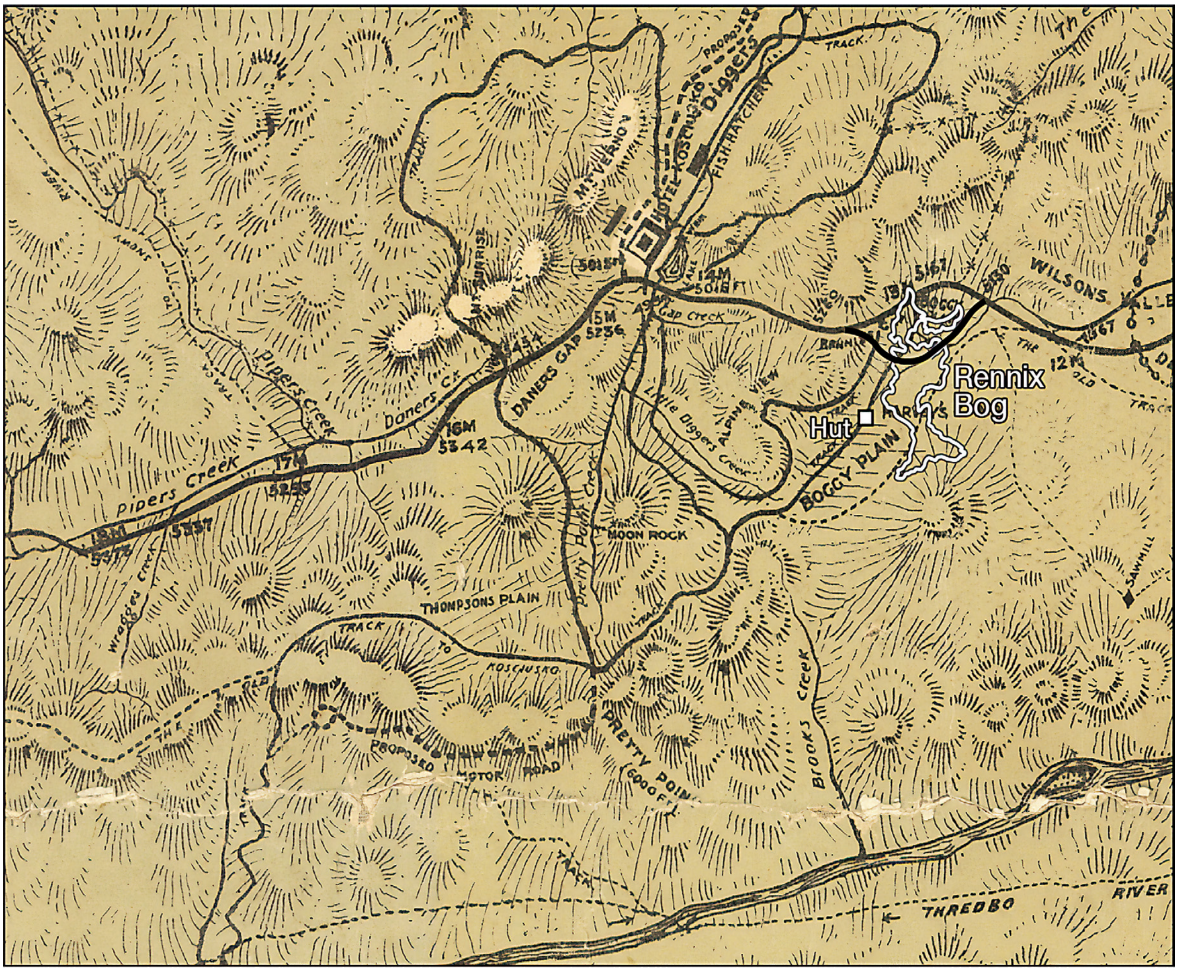


Figure 2. Extract of a Mt Kosciuszko Map from 1909 with the approximate extent of Rennix Gap Bog ("Boggy Plain" on this map) indicated. The black line shows the modern alignment of the road, but the original road skirted the bog to the north.

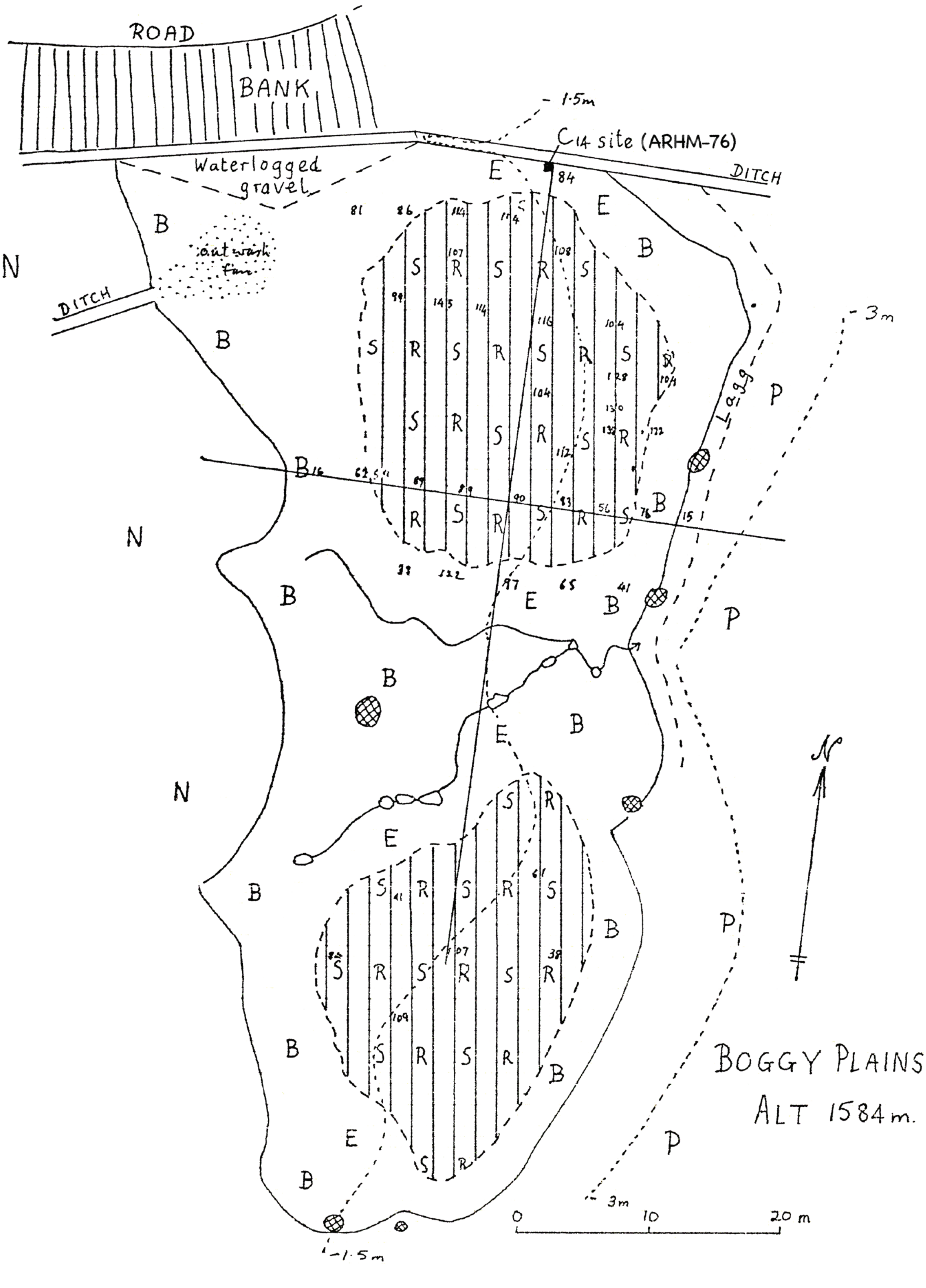


Figure 3. A.R.H. (Tony) Martin's 1959 sketch of a portion of Rennix Gap Bog south of the main road. On this sketch B denotes occurrences of *Baeckea*, *S Sphagnum* and *E Empodisma*..

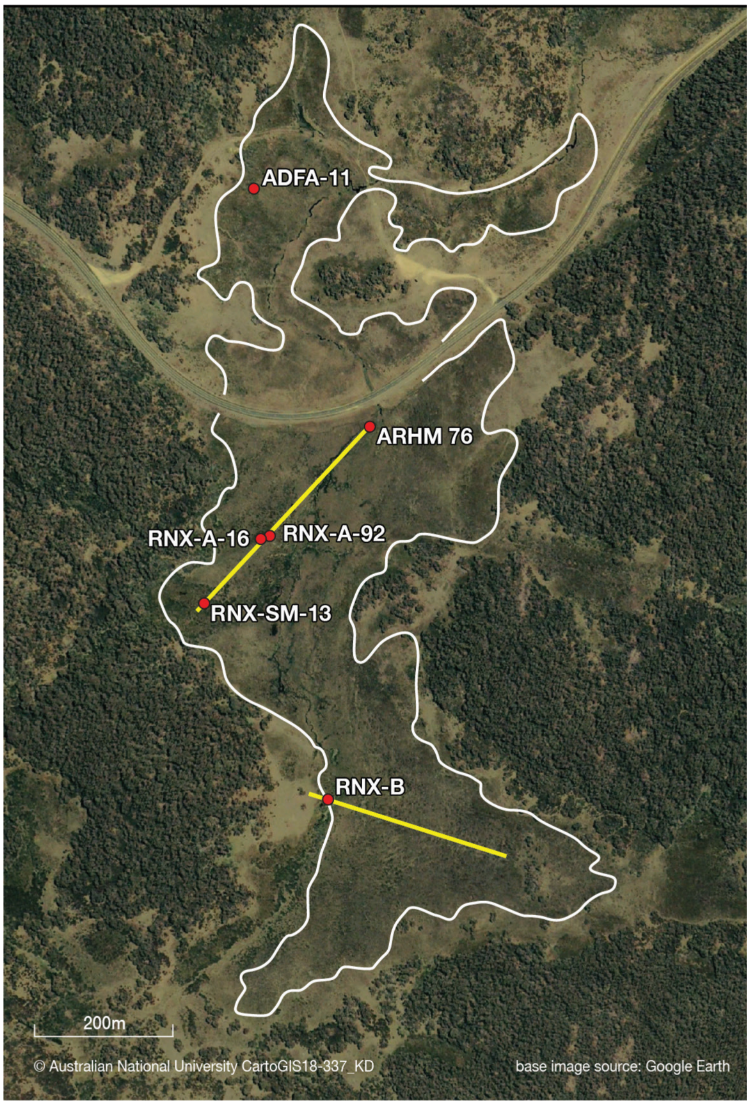


Figure 4. Rennix Gap Bog, showing coring locations and transects mentioned in the text (source: Google Earth Image).

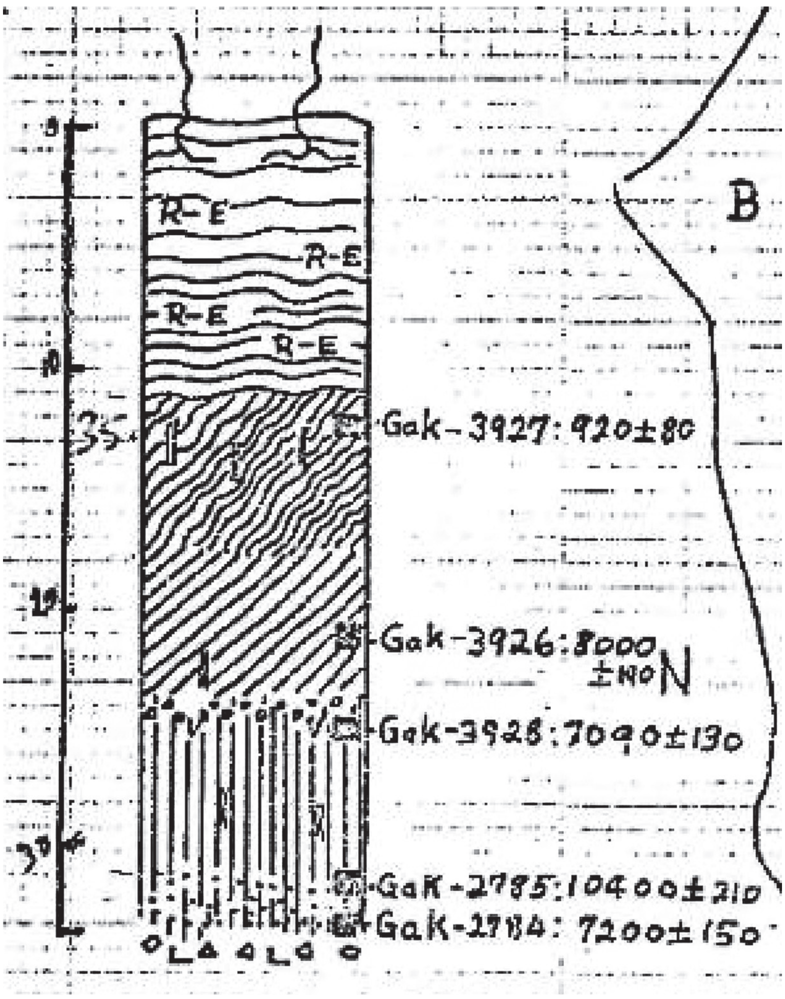
several other Kosciuszko sites (published as Martin 1986b) and on Diggers Creek, a *Sphagnum*-shrub bog at 1720 m, 2.4 km to the southwest of Rennix, which included a brief comparison with Rennix data (Martin 1999).

Rennix Gap is an easily accessible site and has been used extensively for undergraduate teaching. In 1978 Geoff Hope started taking Australian National University (ANU) geography students to the Rennix Gap Bog peatland and returned annually until 1988. During this time, class groups collected information used to describe the stratigraphy across various east-west sections, concentrating on the RNX A and B areas of the swamp, south of the main road, with the most detailed stratigraphic profile across the bog near RNX B (in Figure 4). A single ^{14}C date for the clay-peat interface was completed for the RNX A-80 core which was located about 300m north of RNX B, and a preliminary pollen diagram for the core RNX B-80 was also prepared.

From 1986 similar classes, under the tutelage of Roger McLean, David Gillieson and Stuart Pearson, were undertaken by cadets studying Geography at the Australian Defense Force Academy (ADFA, now UNSW Canberra). This fieldwork, conducted annually until 2015, and sometimes involving more than 100 students, concentrated on the site's geomorphology, landscape ecology and sediment taphonomy using an experiential, hands-on approach. This was originally located close to the Martin cores on the bog, but was subsequently moved, at the request of KNP scientific staff, to the shallower area north of the main road. At about the same time Charles Sturt University (Wagga Wagga) students were also using Rennix Gap for field-based classes, under Ken Page.

In 1993 Justine Kemp undertook research towards her ANU Honours degree under the supervision of Geoff Hope. She studied the late-to-post glacial transition (~20,000-9,000 year sequences) from several sites in the NSW Southern Tablelands and this included Rennix Gap Bog. At Rennix a new sediment core was recovered in the vicinity of the RNX A-80 site to 230 cm depth, revealing an extended clay and sand section overlying weathered granite bedrock below the upper peat. Kemp (1993) completed pollen analysis of the sediments from 90-210 cm, but accelerator mass spectrometry (AMS) ^{14}C dates from the top and bottom of the gravelly sands yielded anomalously young ages. Similarly young ages for mineral sediments underlying peat have been noted in valley bog settings elsewhere in the Australian Alps and may result from contamination by younger organic compounds contained in through-flowing groundwaters (Kemp et al. 2012).

The ADFA and ANU Rennix Gap Bog field activities were followed in upper level classes with microscope-based palynological analyses. At ANU students used samples prepared from the RNX B core and their own samples. In March 2016 ANU



0-32 cm	*Sphagnum* peat with restiad rhizomes
32-44 cm	Black brown humic peat, wood and roots
44-60 cm	Brown sapric peat
60-63 cm	Peat with sand and mica
63-79 cm	Peaty clayey sands
79-85 cm	Peaty sands
Notes: ^{14}C dates were completed at 30-33, 52-54, 62-65, 79-81 and 82.5-85 cm. Additional ^{14}C dates were applied to core 3 (collected *ca.* 1975) at 46-49, 62-65, 75-77, 80-82 and 83-87 cm.	

Figure 5. The stratigraphy of the A.R.H. (Tony) Martin core 2 collected around 1971. In this figure "R – E" indicates Restio-Empodisma rhizomes. The scale on the left hand side is in inches: these have been converted to centimetres in the brief description included below.

undergraduate students (with Janelle Stevenson) re-cored the sediments close to the Kemp site and obtained a 180 cm core (RNX A-16), with the transition from sandy clays to clayey peat at 140-120 cm. ANU undergraduate students quantified charcoal in the core and five samples were ^{14}C dated.

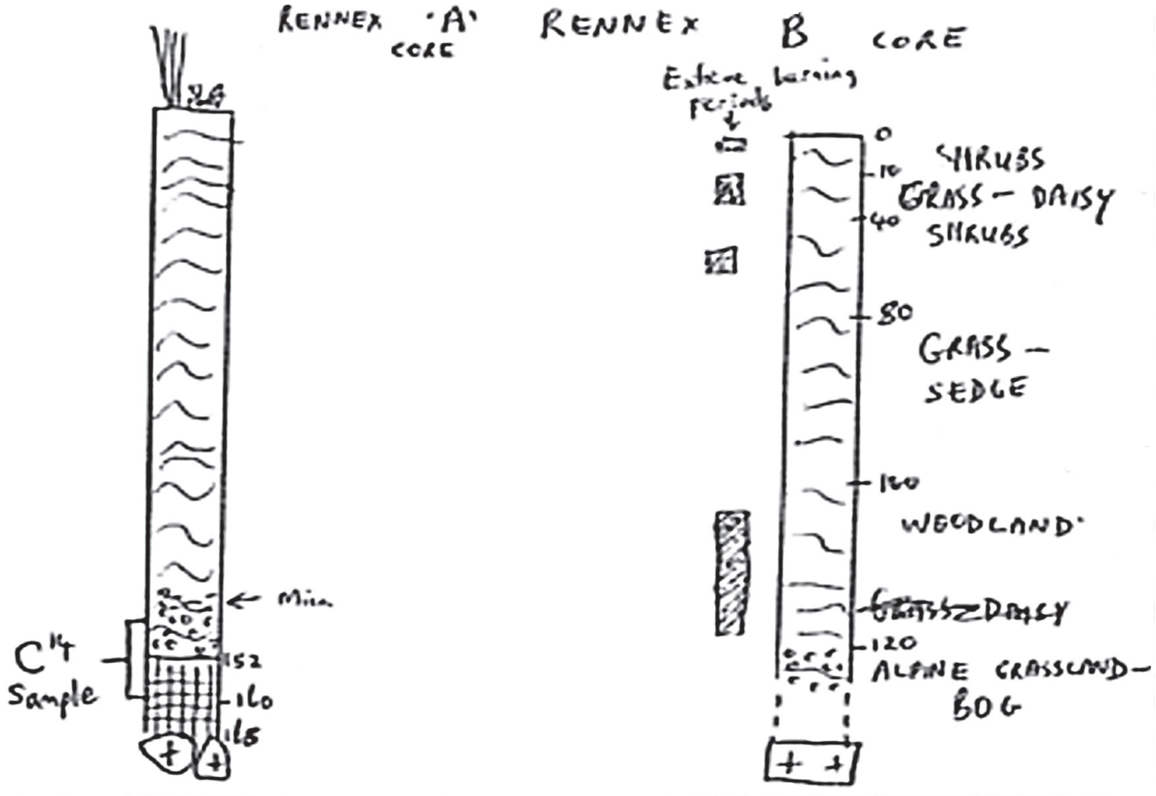
In April of 2013 Scott Mooney (UNSW) began work at Rennix Gap Bog in association with the ARC-funded project *Has 20th Century warming changed southeastern Australia's fire regimes?* (DP12 2012 – 2014). Mooney, Martin and several postgraduate students re-cored the bog on the western margin and obtained a deep peat sequence (to 226 cm). The object of that work was to obtain a detailed fire history from charcoal analysis, and as a part of this Mooney and co-workers radiometrically dated this new core (with 9 lead-210 (^{210}Pb) dates and 6 new AMS ^{14}C dates). As part of this research Patrick Baker and Kathy Allen (University of Melbourne) also undertook dendrochronological research in the Snow Gum woodland surrounding Rennix Gap Bog. This included taking increment cores and quantifying the age of all trees within random quadrats located within a grid with Rennix Gap Bog in the centre.

In 2016 Mooney and UNSW postgraduate student Xianglin Zheng took a series of surface samples across Rennix Gap Bog aimed at quantifying the relationship between environmental parameters (depth-to-water table, moisture content, EC, pH) and the testate amoebae community composition.

RESULTS AND DISCUSSION

Stratigraphy and Dating of the Sediments

Figures 5 to 9 are extracts from field notes and/or lab-based descriptions of the sediments accumulating in Rennix Gap Bog. We have purposely used the original notes of these (where possible), thereby retaining their variegated nature, to reflect the various purposes of the researchers. Figure 10 uses these data to consider



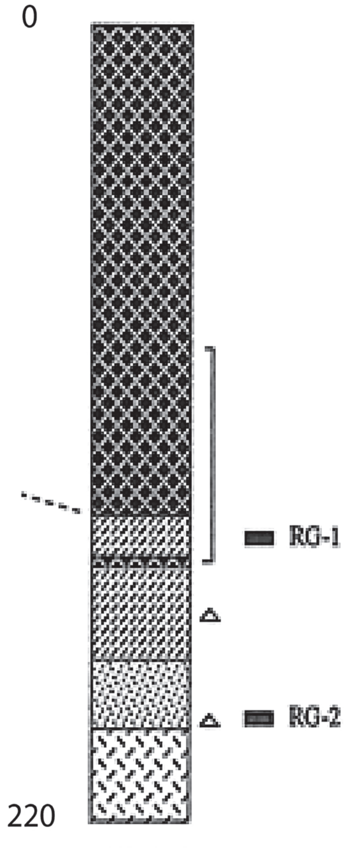
0-135 cm	Black humic peat with root fragments	0-120 cm	Black humic peat with root fragments
135-152 cm	Black humic peat with abundant mica and sand	120-126 cm	Black humic peat with abundant mica and sand
152-168 cm	Grey-brown peaty gravelly sands with abundant mica	126-162 cm	Grey-brown peaty gravelly sands with abundant mica and root fragments
>168 cm	Granite stones		
Notes: One ^{14}C date was analysed from 145 to 160 cm in the Rennix A core. Pollen was analysed to 120 cm.			

Figure 6. A description of the RNX-A-78 and RNX-B core collected 21/3/1978 by Geoff Hope (ANU).

the stratigraphy of the sediments along transects across Rennix Gap Bog.

Table 1 summarises all information about the (radiometric) dating of the Rennix Gap Bog sediments. Examination of the dates shows that there are numerous examples of dating inversions (where a deeper layer provides a younger age than levels above) in individual cores. This is a common problem in shallow peats where roots from younger levels can intrude into older peats and this probably explains inversions in Martin's dates that were based on relatively large slices of bulk peat. The young ages obtained from the sandy clay to peat transition and deeper clay samples in AHRM1976-85, RNX-SM-13-194 and RXA-93-144 and 190 may reflect contamination of sediments with low organic content by traces of younger peats carried down core during sampling or intrusive younger sedge roots. The careful pipetting of charred fragments (RNX-A-16) or identified plant material (RNX-SM-13) from dispersed samples has provided much more reliable age estimates.

The sands and clays underlying small areas of the peatland are the surviving stream deposits that spread across the valley after 15-16,000 years ago, an inference supported by the age of 14,610 ± 375 cal yr BP from the sandy silts at 160 cm in RNX-A-16. This phase of sandy alluviation is also found beneath other



0-90 cm	Dark brown slightly fibrous peat- (not sampled)
90-132 cm	Black humic peat with abundant leaf and root fragments. Water content for this layer exceeds 80% and organic content steadily rises to 50% of the dry weight. Carbonised particles substantially increase after 125cm and peak at 110 cm
132-149 cm	A mixture of grey-brown peaty, gravelly sands with abundant mica and organic debris. Clay minerals include kaolin, gibbsite and poorly-sorted. interlayered clays. Water content steadily increases from 30% at the base to over 50% at the top. Organic content is less than 5% and carbonised particles are insignificant
149-151 cm	This layer consists of brown clayey peats. Water content totals 60% while organic content is 20%. No carbonised particles are recorded
151-178 cm	Grey-brown peaty gravelly sands with abundant mica and root fragments
178-198 cm	Grey gravelly sand with abundant mica
198->220 cm	Weathered granitic saprolite
^{14}C dates: RG-1 144 cm, RG-2 190 cm	

Figure 7. A description of the RNX-A-Kemp core collected in 1993 by Justine Kemp. This core extended to 220 cm and returned pre-Holocene radiocarbon dates (see Table 2): it seemingly was located in a hollow, possibly an old channel, in the underlying sandy plain.

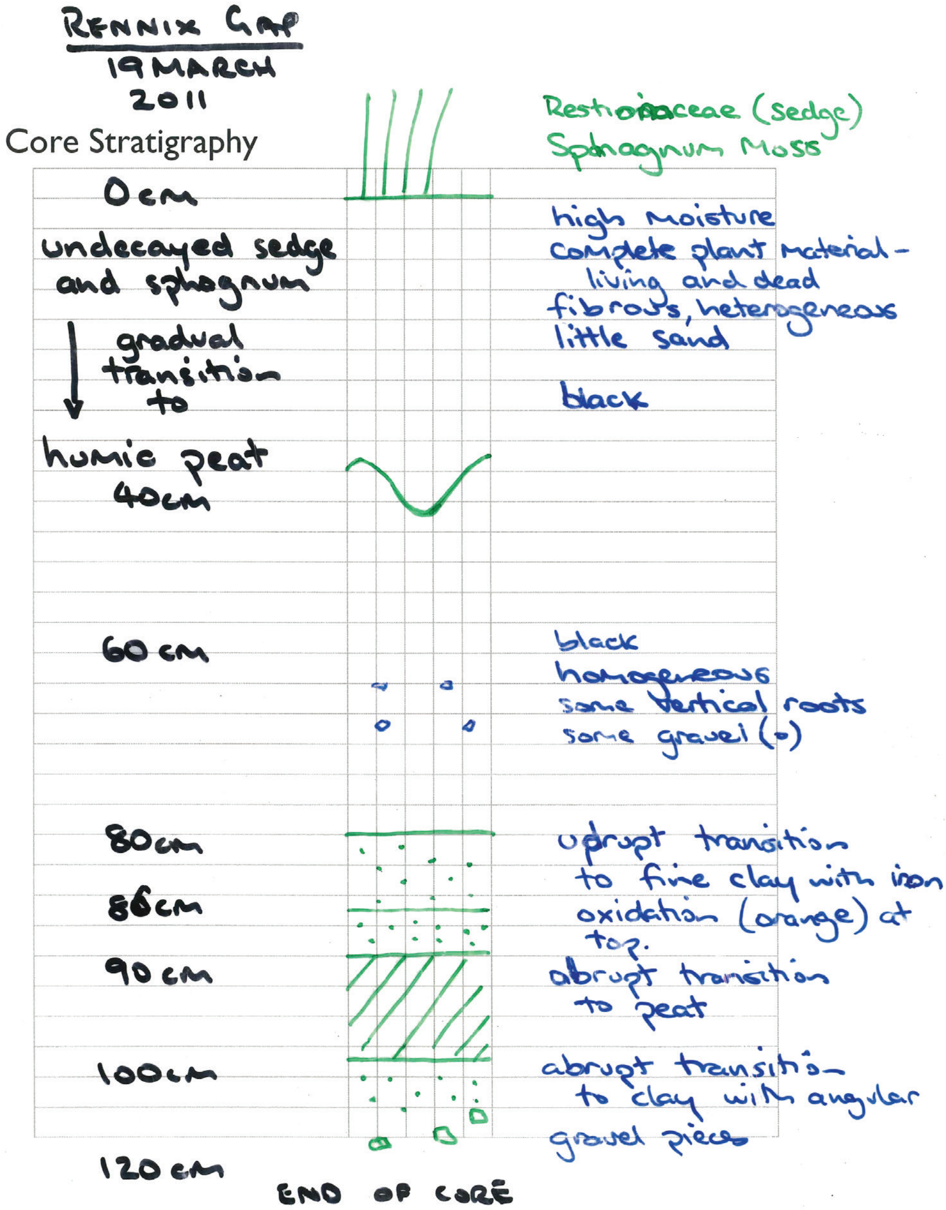
montane and subalpine peatlands in the region (Hope and Nanson 2015) and reflects warming conditions after the maximum cold phase of the last glaciation, identified by Barrows et al. (2002) as 22-19,000 years ago.

The onset of peat formation commenced at Rennix Gap Bog around 12,500 years ago. Dates on bulk peaty sand (RXA-82 and AHRM1960), and macroscopic charcoal particles (RNX-A-16) support this age. Peat probably formed first at the base of the western slopes and along stream lines, gradually spreading onto grasslands on the plain. This result parallels Caledonia Fen in Victoria, at 1280 m, where organic clays abruptly transition to peats at 12,000 ± 485 cal yr BP (Kershaw et al. 2007; 2010). A similar transition occurs at 11,990 ± 485 cal yr BP at Micalong Swamp at 1100m (Kemp and Hope 2014). Increasing moisture and possibly warmth may have controlled this threshold. At Bega Swamp, which is located on the crest of the coastal scarp at 1080 m east of Nimmitabel in NSW, this transition is earlier, at 15,500 ± 350 cal yr BP, perhaps reflecting wetter late Pleistocene conditions there (Donders et al. 2007).

Figure 11 shows a model of the depth-age relationship of the sediments at Rennix Gap Bog, using Bayesian modelling, and a simpler (polynomial) approach, applied to the deepest peat section RNX-SM-13. The depth-age relationship at Rennix Gap Bog (Figure 10) suggests that the net rates of peat accumulation (growth minus decay) are relatively fast in the first few thousand years associated with the early development of the bog, but this rate slows by the mid-Holocene above about 90 cm (representing the last ~8,000 years). The mean resolution of the sediment (near RNX-A) is 42.5 years/cm across the entire profile but the resolution of the recent sediment (e.g. in the Twentieth Century) is approximately 4 years/cm.

Modern Vegetation

The Rennix Gap "bog" is a relatively complex mosaic of *Carex* fen and sub-alpine *Sphagnum*-shrub bog (Hope et al. 2012). The fen component of the site



0-10 cm	Brown living organic material, sedges, pH 4 (5.5)
10-15 cm	Soft fibrous peat, gradual transitions, soft and squidgy
15(20)-30(45) cm	Dark brown humic peat, drier, roots evident, mica crystalline material (evidence of granite derived sediment)
30 (45)-(55) cm	Light grey clay and fine silt, anaerobic, pH 5, sharp transition, (47-56 greens and browns in coarser clay), blue quartz crystals
60 cm	small sharp and angular gravel-sized granite in fine lighter grey clay (green and brown)
70 cm	Light grey grit, soft, dry, yellow stained grey clays
80 cm	White gravel which damaged the corer, pH 5.5

Figure 8. A description of the sediment core ADFA-11 sampled from north of the main road (at 36°21.569’S, 148° 30.244’E) by Stuart Person in 2011.

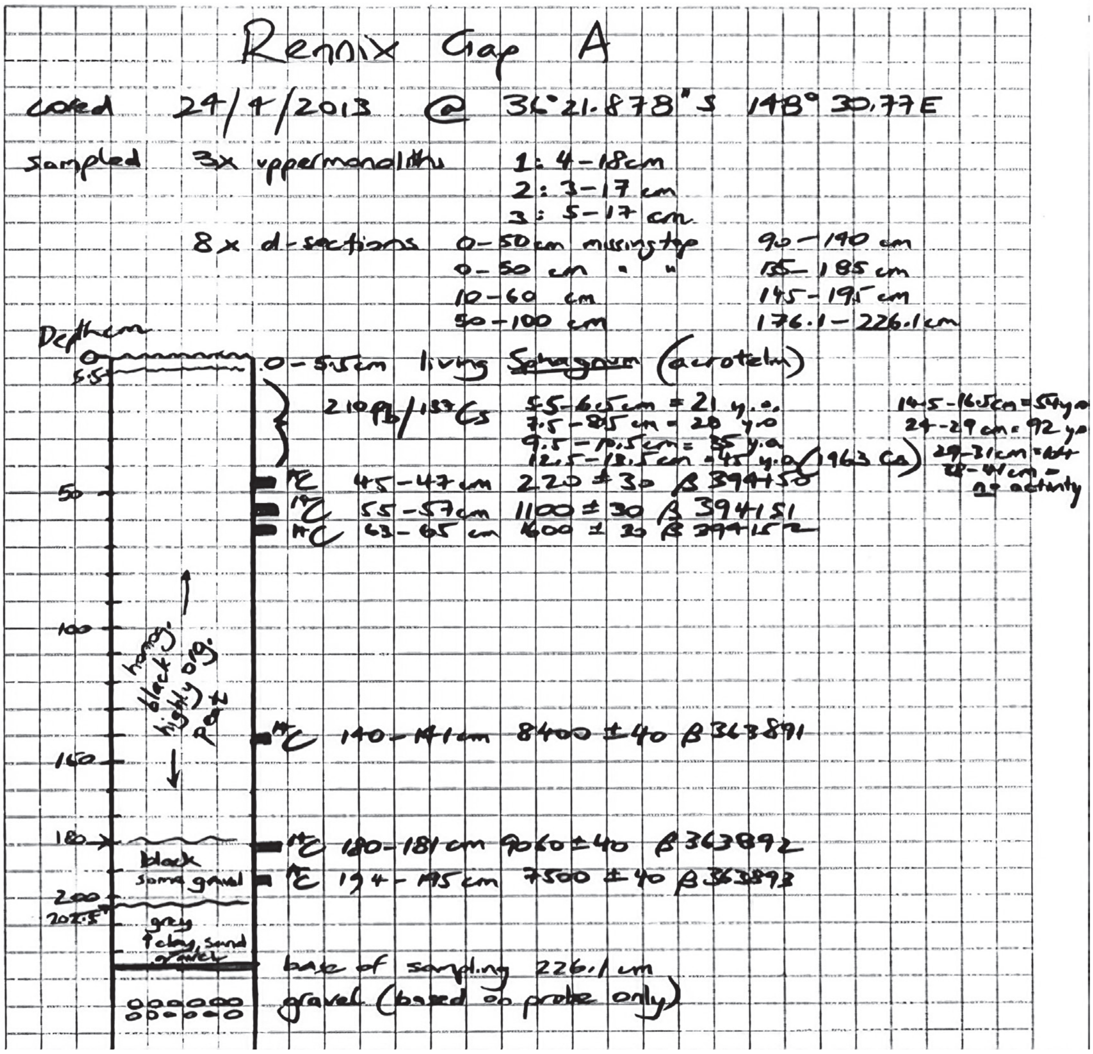


Figure 9. A brief description of the sediment core RNX-SM-13, sampled by a UNSW team in April 2013. This core has been radiometrically dated (see Figure 10) and sampled at a high resolution (0.5 cm contiguous samples from 0 to 60 cm and at 1.0 cm to the base) for the quantification of macroscopic charcoal (>250µm), in Figure 13.

is best described as sedgeland with scattered grasses and herbs in a mat of the sedge *Carex gaudichaudiana*. The sub-alpine shrub bog is variable but marked by shrubs of *Epacris, Richea, Baeckea* and *Callistemon* above *Sphagnum* moss hummocks that are 20-60 cm high. Twig rushes, *Empodisma minus* and *Baloskion australis*, also form dense swards. The shrub-dominated sections of the bog, structurally a heathland (e.g. Specht, 1981), are more common on the western side of the site where shrub height increases to over 1 m. The margins of the peatland are grassy with scattered shrubs and herbs. Many small channels cross the site, and these have aquatic plants such as *Myriophyllum* while *Haloragis micrantha* and *Isolepis fluitans* occupy wet hollows. Table 2 lists the species that we have commonly encountered on Rennix Gap Bog. Part of the peatland was burnt in 2003 but resprouting myrtaceous shrubs and good regeneration by *Epacris* spp has restored shrub cover. *Sphagnum* has recovered more slowly, with old hummocks now often covered by *Empodisma* or grass.

Vegetation History

Kemp worked on a section of basal clays and peat from approximately the RNX-A-site below 90 cm depth that covered the late Pleistocene-early

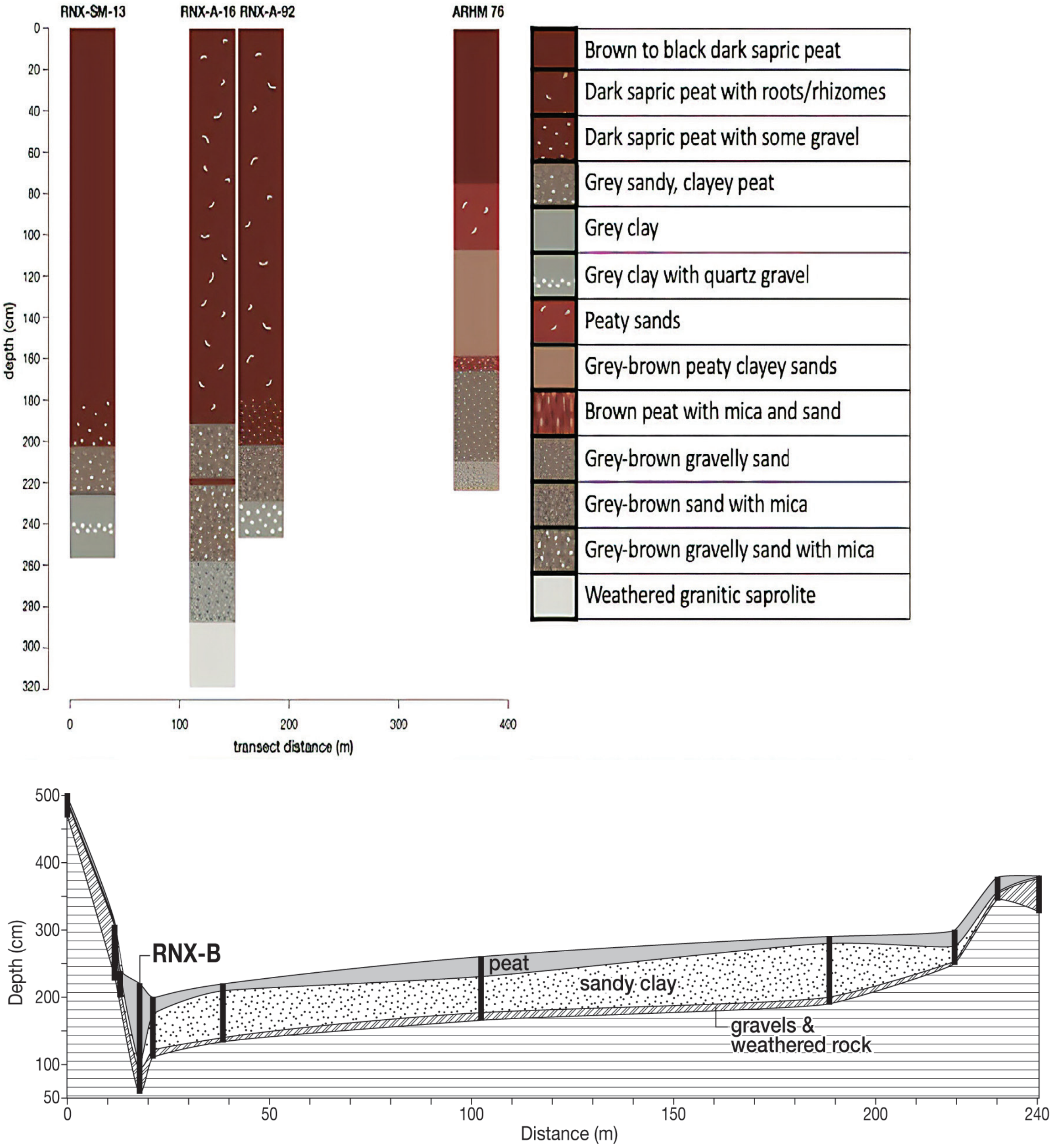


Figure 10. The upper panel (a) summarises the stratigraphy across the northern section of the Rennix Gap Bog and the lower panel (b) is a stylised cross-section showing the stratigraphy of the southern section of the site. The locations of the cross-sections are indicated on Figure 4.

Holocene transition. The dates from RNX-16 provide a consistent chronology, indicating *ca.* 15,400 cal yr BP for the base of the Kemp section at 175 cm. Hope's RNX- B core is undated but has the transition from peaty sands to peat at 120 cm (compared to the same horizon at 132 cm in the Kemp core). RNX-B has been analysed from the surface to 100 cm, providing an overlap that was assessed by comparing the diagrams to allow interpolation of samples. A composite pollen diagram based on the two overlapping sections is summarised in Figure 11. RNX-A-16 and the Martin (ARHM) age-depth relationships are similar above 80 cm giving some support to the hypothesis that the peatland grew consistently in the Holocene. Thus the RNX-16 age model has been applied to the composite pollen record.

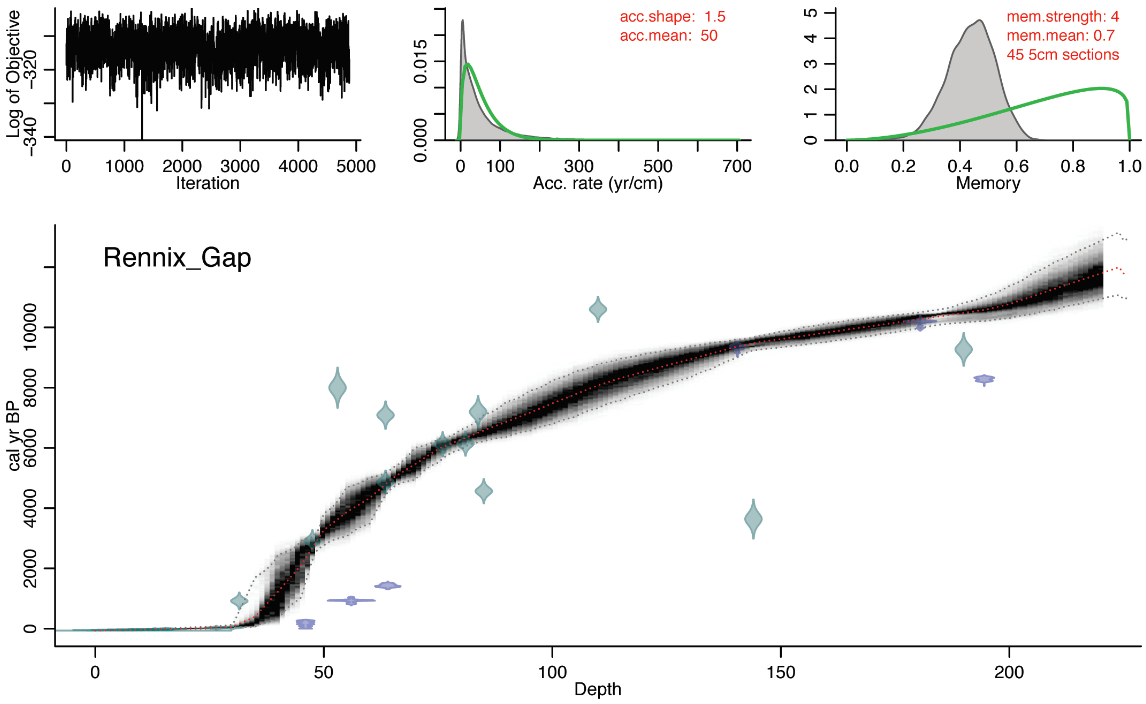
The choice of a pollen sum is difficult in these environments (e.g. Martin 1986b; 1999) and this is true for Rennix Gap Bog as the main woody shrubs on the bog (*Baeckea* and epacrids) dominate some

Table 1. Radiometric ages from Rennix Gap Bog.

Core	Depth (cm)	Dating Method	Conventional Radiocarbon (^{14}C) Age (yrs BP)	Calibrated Radiocarbon (^{14}C) Age (yrs BP)	Likely Age* (calendar years)	Lab no.	Material
ARHM1960	79-81	^{14}C	10400 ± 210	12192 ± 359	BC 10185	GAK 2785	sapric peat
	82.5-85	^{14}C	7200 ± 150	8030 ± 149	BC 6035	GAK 2784	sapric peat
ARHM1972	30-33	^{14}C	920 ± 80	837 ± 76	AD 1155	GAK 3927	sapric peat
	52-54	^{14}C	8000 ± 190	8903 ± 495	BC 6885	GAK 3926	sapric peat
	62-65	^{14}C	7090 ± 130	7910 ± 73	BC 5920	GAK 3928	sapric peat
ARHM1976	46-49	^{14}C	2920 ± 100	3086 ± 139	BC 1070	SUA 563	peat
	62-65	^{14}C	4865 ±110	5606 ± 125	BC 3595	SUA 564	peat
	75-77	^{14}C	6120 ±115	7005 ± 148	BC 5000	SUA 565	peat
	80-82	^{14}C	6145 ±115	6970 ± 290	BC 5035	SUA 566	peat
	83-87	^{14}C	4565 ±115	4240 ± 355	BC 3220	SUA 567	peat
RNX-SM-13	5.5-6.5	^{210}Pb		21 ± 4	AD 1992	ANSTO (P294)	peat
	7.5-8.5	^{210}Pb		28 ± 5	AD 1985	ANSTO (P295)	peat
	9.5-10.5	^{210}Pb		35 ± 6	AD 1978	ANSTO (P296)	peat
	12.5-13.5	^{210}Pb		45 ± 8	AD 1968	ANSTO (P297)	peat
	12.5-13.5	^{137}Cs			AD 1963	ANSTO (P297)	peat
	14.5-16.5	^{210}Pb		54 ± 10	AD 1959	ANSTO (P298)	peat
	24-29	^{210}Pb		92 ± 18	AD 1921	ANSTO (P647)	peat
	29-31	^{210}Pb		104 ± 18	AD 1909	ANSTO (P648)	peat
	38-41	^{210}Pb		No activity	older than AD 1900	ANSTO (P649)	peat
	45-47	AMS ^{14}C	190 ± 30	210 ± 75	AD 1730	β394150	plant material
	55-57	AMS ^{14}C	1070 ± 30	941± 38	AD 1020	β394151	plant material
	63-65	AMS ^{14}C	1580 ± 30	1440± 81	AD 540	β394152	plant material
	140-141	AMS ^{14}C	8370 ± 40	9353± 115	BC 7480	β363891	plant material
	180-181	AMS ^{14}C	9060 ± 40	10193± 58	BC 8280	β363892	plant material
	194-195	AMS ^{14}C	7520 ± 40	8287± 93	BC 6410	β363893	plant material
RXA-82 (Hope)	145-160		10,600±120	12430 ± 220	BC 10530	ANU 2177	peaty sand
RXA-93 (Kemp)	144-145	AMS ^{14}C	3640 ± 185		BC 1970	ANSTO 444	NaOH insol residue
	190-191	AMS ^{14}C	9270 ± 155	10500 ± 195	BC 8480	ANSTO 445	NaOH insol residue
RNX16	50-51	AMS ^{14}C	1634 ± 32	1485 ± 80	AD 469	D-AMS 016367	Charcoal >125 µm
	80-81	AMS ^{14}C	4610 ± 34	5250 ± 195	BC 3265	D-AMS 016368	Charcoal >125 µm
	100-101	AMS ^{14}C	8764 ± 41	9720 ± 170	BC 7730	D-AMS 016369	Charcoal >125 µm
	145-146	AMS ^{14}C	10692 ± 36	12630 ± 70	BC 10685	D-AMS 016370	Charcoal >125 µm
	160-161	AMS ^{14}C	12499 ± 49	14610 ± 375	BC 12652	D-AMS 016371	Charcoal >125 µm

* The "Likely Age (calendar years)" is the median probability intercept with the radiocarbon calibration curve using SHCal13.14c (Hogg et al. 2013), rounded to the nearest half-decade

A



B

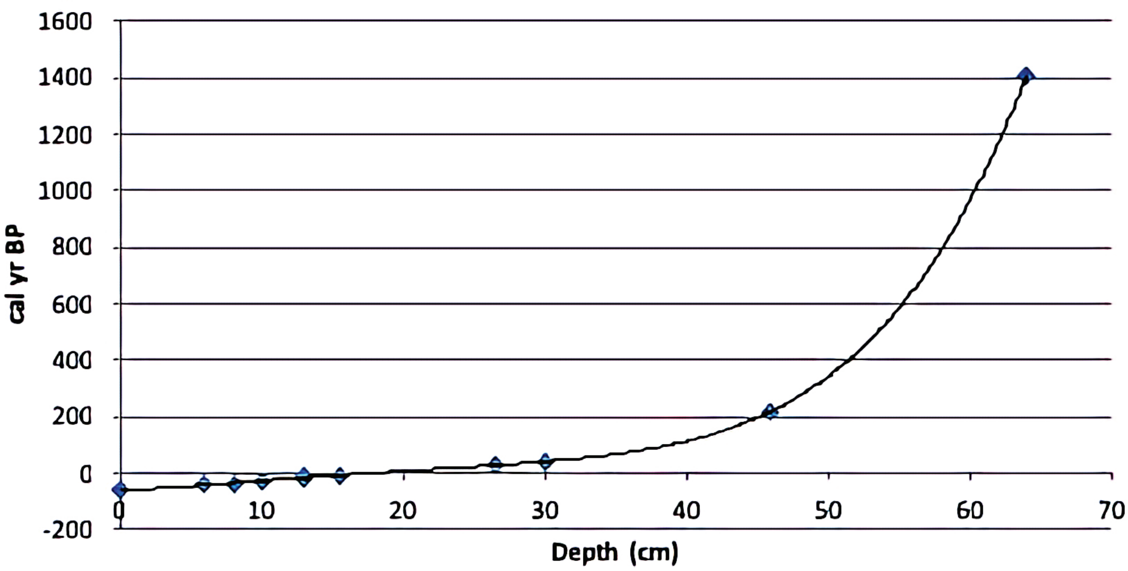


Figure 11. Some depth-age relationships for Rennix Gap Bog. In the top panel (A) all depth-age pairs in Table 2 are used in a BACON age-depth model (Blaauw and Christen, 2011) derived from Bayesian statistics. In this model all dates from across the site are used and hence there is a scatter of results. In the lower panel (B) a (polynomial) age-depth model is developed using only the dates associated with the RNX A locality.

Table 2. A species list generated from field-work at Rennix Gap Bog. The occurrence of these species is delineated to Carex fen, Sphagnum shrub bog or marginal peatland areas. The abundance of the species is described using an ordinal scale: absent -, R= rare or occasional (<5% cover), B= (5-50% cover), C= common (50-75% cover), D= dominant (>75% cover).

Species	**Abundance in Environment**		
	***Carex* fen**	***Sphagnum* shrub bog**	**Marginal peatland areas**
Acaena anserinifolia	-	-	C
Aciphylla simplicifolia	R	-	R
Astelia alpina	R	-	-
Baeckea gunniana	-	D	B
Baloskion australe	D	-	-
Blechnum minus	-	-	B
Brachyscome scapigera	C	R	B
Carex breviculmis	C	-	B
Carex gaudichaudiana	D	-	B
*Centaurium erythraea**	-	-	C
Chionogentias muellerii	-	-	C
Danthonia monticola	-	-	C
Drosera peltata	R	-	-
Empodisma minus	C	D	-
Epacris brevifolia	-	C	-
Epacris paludosa		C	B
Epilobium billardierianum subsp. *hydrophilum*	R	C	B
Galium gaudichaudii	-	-	C
Geranium neglectum	-	-	C
Hakea microcarpa	-	-	C
*Holcus lanatus**	R	-	C
Hydrocotyle laxiflora	R	R	-
Isolepis fluitans	C	-	-
Juncus falcatus	C	-	C
Leptospermum lanigerum	-	-	C
Luzula sp	-	-	B
Myriophyllum pedunculatum	C	-	-
Nertera	R	-	R
Poa costiniana	-	-	D
Poa sieberiana var. *cyanophylla*	-	-	C
Ranunculus	C	C	C
Ranunculus (?Caltha)	R	-	-
Richea continentis	-	C	-
Sphagnum cristatum	-	D	-
Stellaria pungens	-	-	C
Utricularia dichotoma	-	R	-

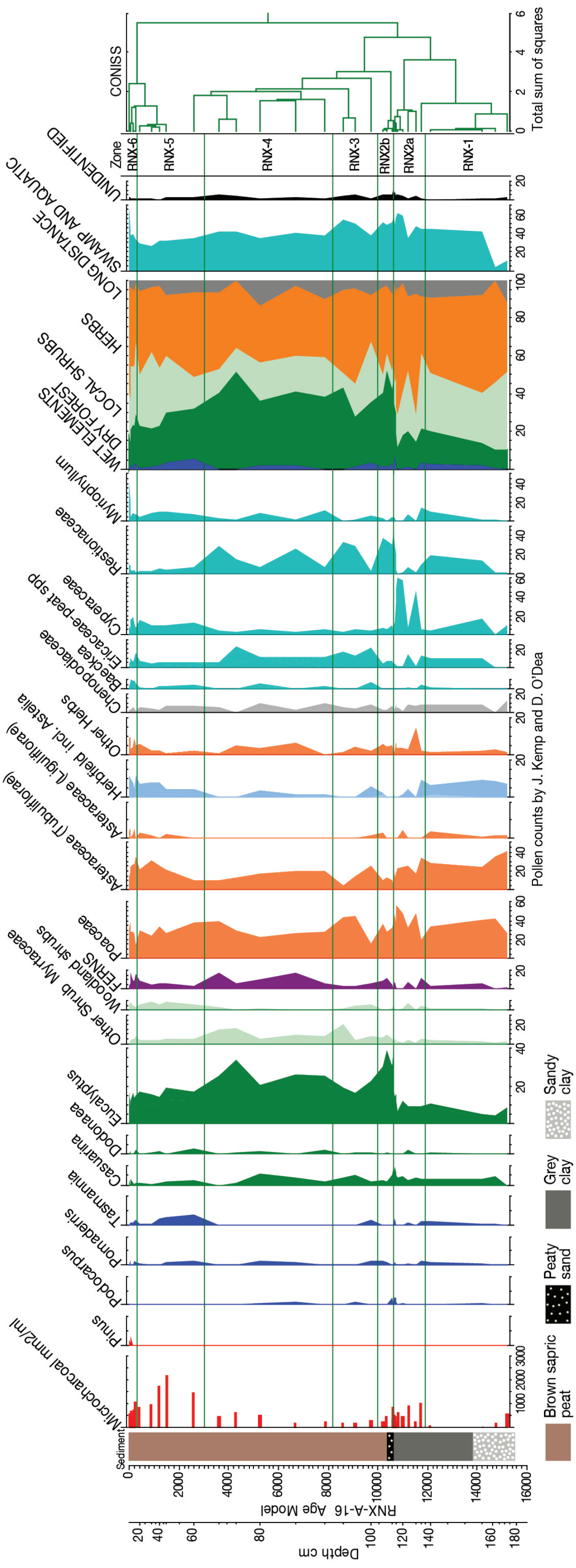


Figure 12. Composite pollen diagram from Rennix B and core RNX-A. The radiocarbon chronology is interpolated from the cores from ARH Martin (Core 2). Justine Kemp completed the palynology.

sediment horizons. These have been excluded from the pollen sum in Figure 12, together with sedges and *Myriophyllum*. Herbs and grass are included in a dryland pollen sum against which individual pollen percentages are calculated.

The basal zone of Figure 12 is dominated by an alpine grassland-herbfield with abundant daisies and sedges. A slow increase in eucalypt representation is evident from 15 to 11,600 years ago and in this basal section the site is a sedge fen. The presence of significant liguliflorous daisy pollen suggests that the herb-rich alpine grasslands supported abundant myrnong (*Microseris* sp. see Gott 2008) even though it was presumably much colder than the present day. These palaeoenvironmental data suggest that Rennix Gap may have resembled the contemporary eastern slopes of Mt Twynham. Fire is rare in this zone. At 11,600 cal yr BP fire increases and grass increases at the expense of herbs and daisies. The bog becomes a sedgeland and the increase of eucalypts stabilizes until around 10,600 cal yr BP.

At this time an abrupt increase of eucalypts in the upper 15 cm of sandy peats and lowest 10 cm of peat marks the arrival of the Snow Gum woodland and a very clear transition of the treeline. Grass, daisies and herbs decline and fire is also less marked. The grassland around the bog records an increase of daisies relative to grass. This situation is stable from 8500 cal yr BP until around 3000 years ago when shrubs and trees decline and herb-rich grasslands expand. These changes might represent either the retreat of the woodland edge (away from the coring location) or the opening out of the woodland canopy. The peatland experiences rising sedge cover at the expense of bog taxa such as Ericaceae and *Empodisma*. Fire may be implicated as charcoal increases in the upper zones.

European influences appear only in the upper 10 cm (of the Figure 12 pollen) with reductions in eucalypt cover and fluctuations in grass and the

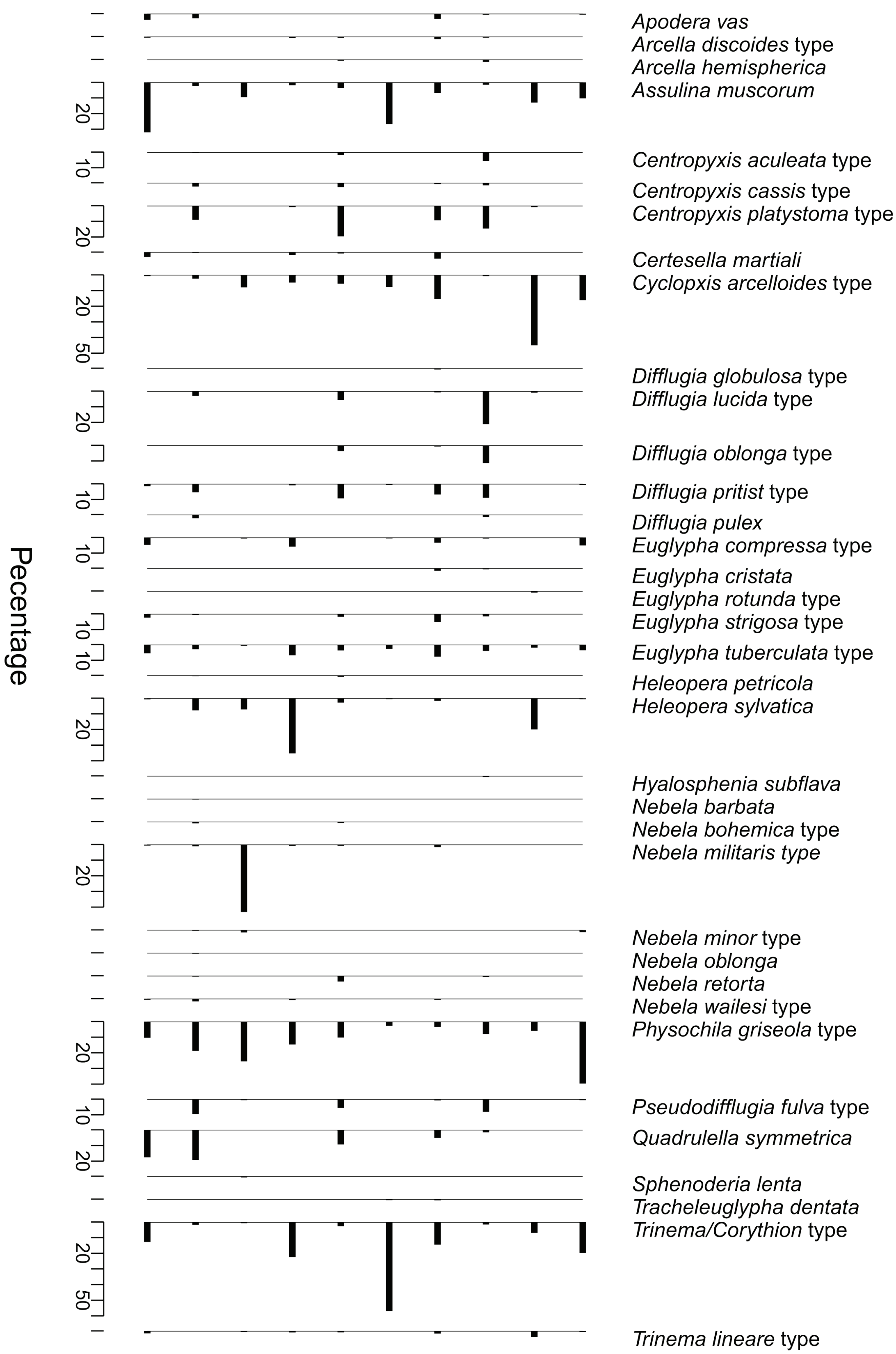
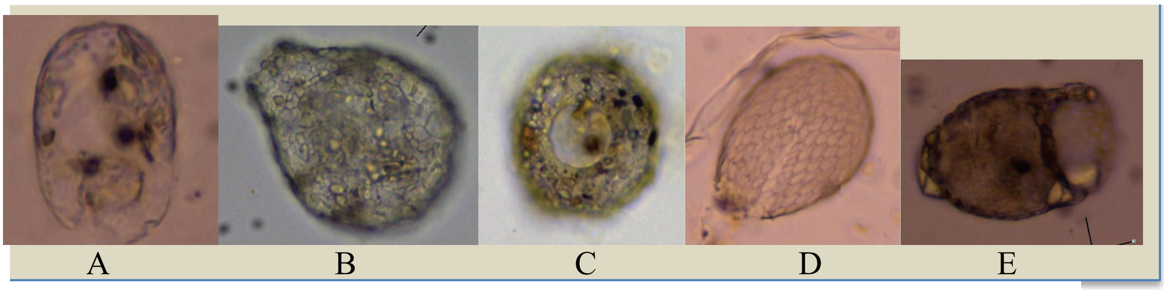


Figure 13. Testate amoebae from Rennix Gap Bog. In this diagram the vertical axis represents the 10 surface samples taken from across Rennix Gap Bog. The images on the following page show some of the common testate amoeba from the site.



Key:
A *Trinema/Corythion* type (length: 48µm)
B *Physochila griseola* type (length 74µm, breadth 59µm)
C *Cyclopyxis arcelloides* type (radius 38µm)
D *Centropyxis playstoma* type (length 61µm, breadth 31µm)
E *Assulina musocurm* (length 44µm)

Figure 13 continued - some of the common testate amoeba from the site. Analysis by Xianglin Zheng (UNSW).

daisies. The fen expands further at the expense of bog, possibly reflecting damage associated with the grazing by cattle.

Testate Amoeba at Rennix Gap

Testate amoebae have been used extensively in the Northern Hemisphere for quantifying depth to water table (DWT) in peat (Mitchell et al. 2008, Amesbury et al. 2016) and hence are one of only a few moisture sensitive proxies. There has been limited research on testate amoebae in Australia, with only two publications on their modern ecology (Meisterfeld and Tan 1998, Bamforth 2015). Figure 13 depicts the testate amoebae sampled across Rennix Gap. From this work the following species have been identified as common on the site: *Trinema/Corythion* type, *Physochila griseola* type, *Cyclopyxis arcelloides* type, *Centropyxis playstoma* type and *Assulina musocurm*.

Fire History: Charcoal and Dendrochronology

Microscopic charcoal was counted by Kemp and O'Dea from the composite record at ca. 10 cm intervals (Fig. 12). Interestingly these small charcoal particles were found in the basal clayey samples examined. While these may reflect long distance transport, they could also suggest that fire was a part of the above-treeline grasslands of the late Pleistocene. They found a distinct increase in charcoal around 3,000 cal yr BP, which coincided with a decline in *Eucalyptus* representation. This is a feature seen in other mires in the region.

The high-resolution macroscopic charcoal records are presented in Figure 14. In comparison to the microscopic charcoal record (Figure 12) no macroscopic charcoal was found in the basal sediments (below 202 cm or 10,875 cal y BP). Tthis may represent the depositional environment (noting that this depth corresponds to the transition to gray, clayey, gravelly sediments in Figure 9) or it might describe that local fire 'turned on' in this environment at about 10,800 years ago as the Snow Gum woodland was established. The late Pleistocene-early Holocene period revealed consistently high fire activity, a feature that is shared with other fire records from eastern Australia (e.g. Black et al. 2008). The mid-Holocene shows a remarkable lack of fire activity, and this then switches back on at about 4,300 cal yr BP. Fire activity in the historic period clearly exceeded that of the centuries that preceded it (Fig 14 C). Fire frequency seems to have peaked in the early historic period (~1840), declined into the early Twentieth Century and but has risen again in the recent past.

Figure 15 shows the dendrochronological record of fire in the woodland surrounding Rennix Gap Bog. The dendro-record revealed that the woodland is mostly relatively young and reflects the regeneration after the 1939 fires. Fire events in the Twentieth Century are often patchy, with some quadrats clearly burnt and other adjacent plots unburnt. The exceptions are the fires of 1954 and 2003, which burnt all of the quadrats analysed.

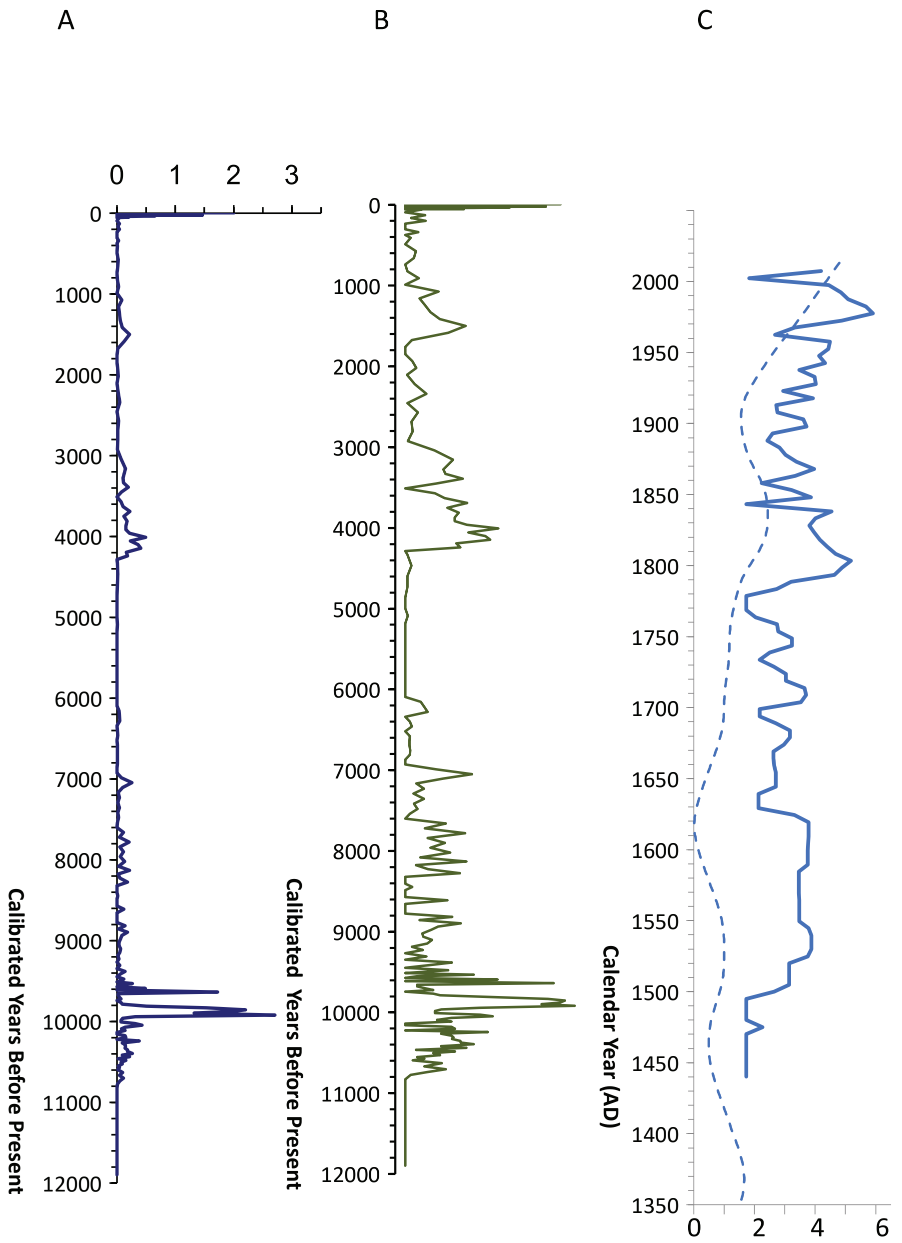


Figure 14. A high-resolution record of macroscopic (>250 µm) charcoal from Rennix Gap Bog, representing fire at a local scale. Panel A shows the accumulation of macroscopic charcoal (CHAR as number of particles/cm2/yr) against the weighted mean age (calibrated years Before Present) inferred from the BACON in Figure 11. Panel B shows the same data, but charcoal data have been transformed to reveal fine details. Panel C shows the recent history of CHAR (solid line) and the inferred fire frequency (dashed line, scale on bottom in fires per 250 years) at Rennix Gap over the last ~500 years, with the vertical axis representing calendar years (AD).

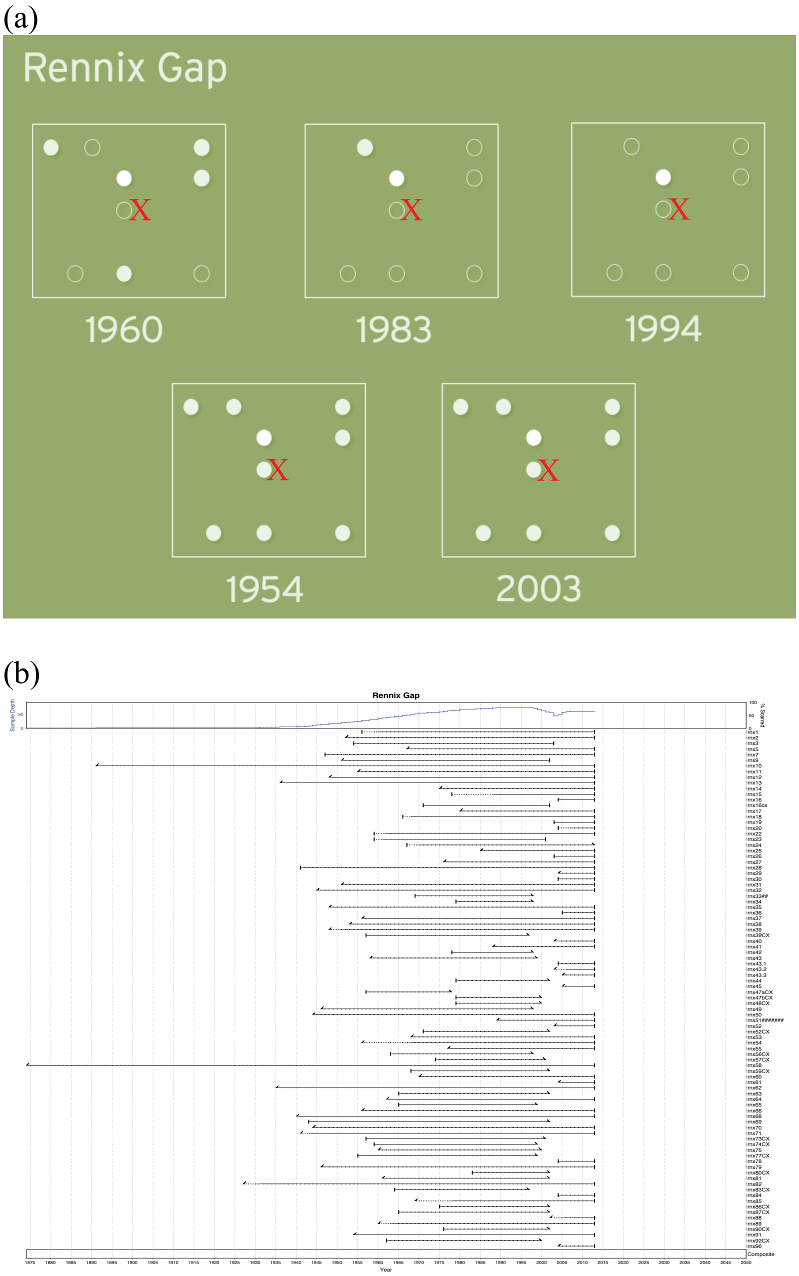


Figure 15. Some of the results from the dendrochronological study in the Snow Gum woodland surrounding Rennix Gap Bog. In the top (a) diagrams Rennix Gap Bog is in the centre (X) and the circles represent quadrats where a complete inventory of the Snow Gum population was undertaken. The open circles represent plots were fire was not recorded and the filled-in circles represent fire in that year. The years in this diagram were chosen to compare the record of fire from sedimentary charcoal with the dendrochronological information: the top row are years with charcoal peaks but little evidence of fire in the Snow Gums and the bottom row are fire years with little charcoal. This mis-match between dendro-perspectives and sedimentary charcoal represents relatively small uncertainty with radiometric dating of the sediments (versus high precision in dendrochronology) and charcoal taphonomy. In (b) the dendrochronological age of the sampled Snow Gum cohort is shown, demonstrating that most trees are relatively young and the oldest is something like 140 years old (in 2015).

Debate concerning the management of fire in Australia's high country and in the forested montane ecosystems and agricultural lands that surround these ecosystems at lower altitudes has a history now exceeding 100 years (e.g. Helms 1893). Debate has particularly raged in the period since the 2003 conflagration, which engulfed the high country and surrounding lands. This work demonstrates that European pastoralists brought significant changes to the fire regime in the Snowy Mountains.

Until recently, the marginal environment and limited food resources (but *cf.* Argue 1995, Gott 2008) of the south-eastern highlands were thought to be responsible for the supposed relatively recent Aboriginal occupation of the highlands (Flood 1980, Flood et al. 1987). It is hence tempting to link the increase in fire activity at about 4000 cal yr BP (Figure 14) to this postulated occupation but evidence of humans at Birrigai at ca. 21,000 yr BP (Flood et al. 1987), at only 730 m altitude but on the northern fringes of the south-eastern highlands in Tidbinbilla Nature Reserve, means that a much longer occupation of the high country must be at least entertained. This conclusion is also justified by archaeological evidence in Tasmania where Aboriginal people were unequivocally occupying alpine-type environments associated with the LGM in Tasmania (Cosgrove et al. 1990, Flood 1995). The new evidence for early Holocene occupation around 1100m mentioned earlier (Theden Ringl 2017a) also supports a long history for human interaction at still higher altitudes. It is hence more likely that fire in the pre-European environment reflects climatic controls with the mid-Holocene changes associated with increasing climatic variability. This also corresponds with ideas by Richard Helms (1893) (and others: Banks 1989, Pyne 1991) who described the high country as free from fire before the advent of the pastoralists' pyromania.

Relatively recent changes in the flora of the Kosciuszko National Park *Sphagnum* peatlands has been considered by Clarke and Martin (1999) and Clarke et al. (2015). They demonstrated some temporal trends over about 50 years but concluded that the mountain mires are relatively resilient, especially to single fire events, but that recovery from grazing is a slower process. This resilience is, however, untested with the likely combined impacts of future climate change, any enhanced fire regime (e.g. frequency, intensity, area burnt) and recovery from past events.

Conclusions: Research and Teaching at Rennix Gap Bog

The Rennix Gap area is important because it provides palaeoenvironmental information for a sub-alpine Snow Gum-dominated vegetation community. It is located at an altitude that it was geographically close to the Kosciuszko ice cap during the Last Glacial Maximum (LGM), which occurred at about 22- 21,000 years ago (Barrows et al. 2002). A late LGM glacial advance at ~19,100 years ago (the Blue Lake Advance) is apparent in the Snowy Mountains (Barrows et al. 2002) and post-glacial warming began after about 17,800 cal. BP (e.g. Menviel et al. 2011). It seems that the modern sub-alpine Snow Gum-dominated environment at Rennix Gap dates to about 10,600 years ago, and that the late glacial period was characterised by a grassland-herbfield community. The Rennix Gap Bog studies also provide a long temporal perspective on fire in this landscape; allowing, for example, a comparison of pre- and post-grazing burning regimes. Comparing the recent sedimentary charcoal records with fire scars on old Snow Gums also provides information on charcoal that is applicable at much broader spatial scales.

Rennix Gap Bog has also been an invaluable teaching resource. Staff working in Rennix Gap Bog never tire from seeing the amazed students' faces as they see evidence of change, from periglacial debris flows to current environments clearly reflected in the changing sediments. Recently it has been a powerful reminder to students that the magnitude and rate of changes anticipated for the next fifty years may exceed those recorded in the core. This field work has thus made incomprehensible periods of time and environmental change through time "real" for students in a way that cannot be replicated in classrooms or virtual reconstructions. An important aspect of this has also been the involvement in ongoing research rather than simple exercises.

This same sense of deep time is one of the rewards that the national parks system can convey to visitors through their educational facilities and outreach. A helpful explanatory notice that has been placed on the "Rennix Walk" track that crosses the northern part of the bog on the old road before turning north currently omits much of the scientific knowledge that is available, as summarised in this paper. There is also scope for a "peatland walk" at Rennix Gap Bog that would introduce the modern and former environments to the interested public.

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