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Accumulation and attrition of peat soils in the Australian Alps: Isotopic dating evidence

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Abstract Bog peat soils have been accumulating at Wellington Plain peatland, Victoria, Australia for the last 3300 years. Now, dried peat soils are common adjacent to bog peats. The ^{14}C basal age of dried peat is not different from the ^{14}C basal age of bog peat, which supports the theory that dried peat formed from bog peat. A novel application of ^{210}Pb dating links the timing of this change with the introduction of livestock to Wellington Plain in the mid-1800s. Physical loss of material appears to have been the dominant process removing material as bog peats drained to form dried peats, as indicated by the mass balances of carbon and lead. This research has implications for the post-fire and post-grazing restoration of bogs in Victoria's Alpine National Park, and the contribution of peat soils to Australia's carbon emissions.

Key words: carbon dating, grazing, lead dating, peat, wetland.

INTRODUCTION

Peat soils form where decomposition is hindered, often by a combination of cold and wet conditions, such that production of organic matter outweighs decomposition. Such conditions are rare in the hot, dry continent of Australia. Consequently, peat represents a small proportion of the Australian landscape, although small areas are noted to occur in the Alps and along the humid east coast (McKenzie *et al.* 2004). While lowland peats have largely been drained for agricultural use, much of the peat located in the Australian Alps resides within National Parks. Small areas of bog peat (Grover & Baldock 2010) are locally common in alpine and subalpine catchments, as peat-forming vegetation is adapted to the wet conditions beneath springs and seepage zones. Shallow, dried peat soils (Grover & Baldock 2010) are also extensive in these alpine regions, sometimes adjacent to bogs and elsewhere surrounded by mineral soils.

Australian alpine peats were first described by Costin (1954), who proposed that dried peat formed from a parent material of bog peat, drained either by past climatic warming, or by recent trampling by introduced livestock. Livestock were grazed over summer in the Alps from the mid-1850s (Cabena 1980). Dried peats formed recently were thought to occur adjacent to bog peats, while dried peats formed by past climatic warming were thought to occur independently of bog peats and be surrounded by mineral soils (Costin 1954). This theory of the origin of dried peat is based on field observations, environmental history research and an understanding of how bogs function, based primarily upon theories developed to explain peat formation in Europe (Costin 1954; Costin *et al.* 1959). Alternatively, dried peat adjacent to bog peat could be the result of two periods of bog formation (David Ashton, pers. comm., 2003). Under this scenario, dried peat is the remnant of an earlier period of bog formation, and the entire bog drained due to climatic warming. Subsequent wetter conditions initiated a second period of bog formation, on top of the dried peat (David Ashton, pers. comm., 2003).

Peat soils in the Australian Alps have received renewed attention following the extensive fires of 1998 and 2003, and the cessation of cattle grazing in the Victorian Alpine National Park in 2005. Peatland restoration works, involving weirs and planting/transplanting, are underway in Victoria, New South Wales and the Australian Capital Territory (Wahren & Papst 1999; Hope *et al.* 2005). Any attempt to restore an ecosystem ought to be based on a sound knowledge of the original state of that ecosystem.

The research presented in this paper investigates the origin, accumulation and attrition of peat soils on Wellington Plain in the Victorian Alps. We aimed to examine: (i) the rate of peat formation; (ii) whether or not bog peat is the parent material of dried peat; and (iii) the timing and mechanisms associated with dried

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peat formation. We applied techniques of isotopic dating and mass balances of carbon and lead to investigate these questions. Our novel application of the ^{210}Pb dating technique to adjacent intact and disturbed cores is of broad relevance as it could potentially be applied to other partially disturbed ecosystems.

METHODS

Site description

The Australian Alps are the highest parts of the Eastern Highlands (Ollier & Wyborn 1989). This area covers roughly 0.3% of mainland Australia, and includes land from 200 m above sea level to the peak of Mt Kosciuszko at 2228 m (Costin 1989). Not all of the Alps is alpine, and areas that experience persistent snow constitute only 0.07% of mainland Australia (Costin *et al*. 2000). High plains are a characteristic feature of the Australian Alps. Due to drainage of cold air down the adjacent slopes, these high plains support treeless subalpine vegetation similar to the alpine vegetation found above the tree line. The low relief and high rainfall of the high plains make them particularly well situated for the development of wetlands, and peatlands constitute 10% of the Bogong high plains (McDougall 1982) and 5.8% of the Kosciuszko alpine area (Costin *et al*. 2000). Peatlands occur along valley bottoms and beneath springs and seepages where groundwater reaches the surface.

Our study was located at Wellington Plain peatland with the purpose to build upon knowledge of peatland function ensuing from the peatland restoration research begun there after the Caledonia Fire in 1998 (Wahren & Papst 1999). Wellington Plain, in the south-east Gippsland Alps (Fig. 1), is underlain by two rock types: sedimentary rock from the lower Carboniferous/upper Devonian, and acid volcanic rock from the upper Devonian (Rosengren 2002). Wellington Plain peatland (484950 5849700 on map 8223-S (Tamboritha-Moroka), AMG 55) covers an area of approximately 43500 m^2 at 1480 m a.s.l. and experiences snow-lie for 1–3 months of the year. The average monthly maximum and minimum temperatures in 2004 and 2005 were 12.3°C and −2.3°C and 12.7°C and −1.3°C, respectively. Annual rainfall in this area of the Alps is estimated to be about 1270 mm (Rowe & Downes 1960).

The characteristic vegetation of the bog peat is *Sphagnum cristatum*, *Empodisma minus*, *Baloskion australe*, *Epacris paludosa*, *Richea continentis*, *Baeckia gunniana*, *Astelia alpina* and *Carex gaudichaudiana*. The characteristic vegetation of the dried peat is *Empodisma minus*, *Baloskion australe*, *Poa costiniana*, *Epacris paludosa*, *Baeckia gunniana* and *Carex gaudichaudiana*. Thus, there is much overlap of species, with the notable exceptions of a lack of the hydrophilic *Sphagnum* on the dried peat and a lack of the less-waterlogging-tolerant *Poa* on the bog peat.

Profiles of the two most extensive peat types, bog peat (Fig. 2) and dried peat (Fig. 3), were photographed and described from soil pits dug. Nomenclature follows the Australian Soil Classification (McDonald *et al*. 1990; Isbell 1996) and the von Post humification (V.P.H.) scale (reproduced in Armstrong & Castle 1999). The profile photos and descriptions in Figures 2 and 3 show two quite different soils. The bog peat was dominated by fresh organic material, which gradually became darker and less fibrous with depth,

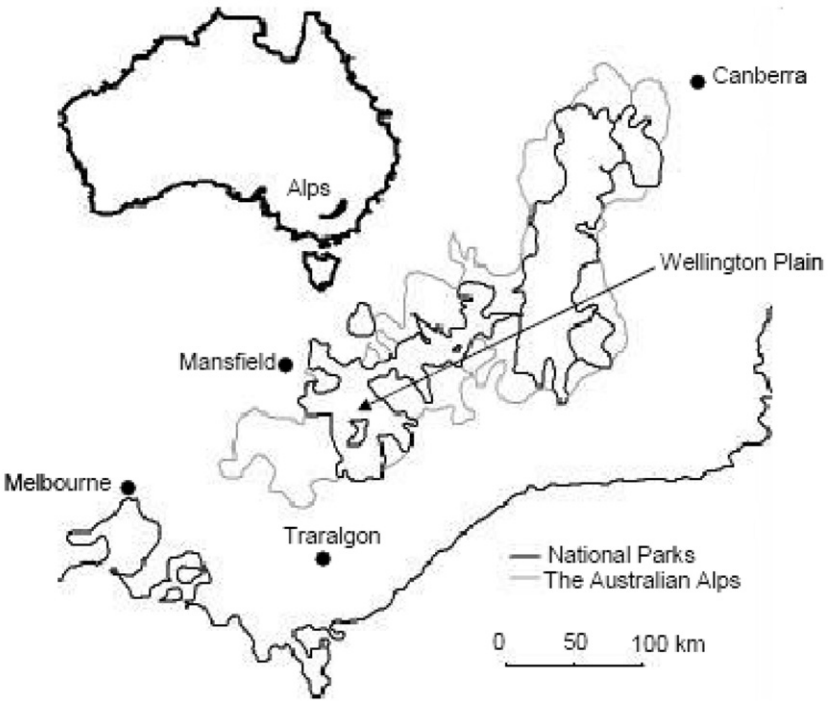

Fig. 1. The location of Wellington Plain in the Victorian Alps and (inset) the Alps in Australia.

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Depth (cm)	Description
0-50	Fibric peat, V.P.H. 3, gradual change from live green *Sphagnum* to dead fawn coloured (2.5Y7/8) *Sphagnum*, plant matter totally intact. Clear water was squeezed out. Gradual boundary.
50-85	Hemic peat, V.P.H. 5, colour change from fawn (2.5Y7/8), through light brown to medium brown (10YR4/4). Much plant matter still recognisable, but beginning to decompose. Peat becomes less fibrous down the profile. Brown water was squeezed out. Gradual boundary. Watertable at 65 cm.
85-140	Sapric peat, V.P.H. 9, thick black viscous liquid (5YR3/2). Thoroughly decomposed, some woody roots. All material was squeezed out through the hand.

Fig. 2. Profile description and photo of bog peat. V.P.H., von Post humification.

Depth (cm)	Description
0-4	Hemic peat, very dark brown (10YR2/2), very weak non-sticky consistence, weak 2.5 mm polyhedral structure, fine roots abundant, medium roots many, sharp boundary.
4-13	Sapric peat, black (10YR2/1), wet, weak non-sticky consistence, weak 2.5 mm polyhedral (granular) structure, fine roots abundant, medium roots many, gradual boundary.
13-23	Peaty light clay, black (2.5Y2/1), wet, slightly sticky, slightly plastic, weak to moderate 2-5 mm sub-angular blocky structure, fine roots many, medium roots common, clear boundary.
23-28	Light clay, dark grayish brown (2.5Y4/2), yellowish brown (10YR5/8) mottles common, 3 mm apedal to weak 5-8 mm sub-angular blocky structure, fine roots few, over gravel.

Fig. 3. Profile description and photo of dried peat.

as the material became more decomposed (V.P.H. 3 to 9). The three peat types recognized by the Australian Soil Classification (Isbell 1996) were present: fibric, hemic and sapric peats occurred sequentially down the profile. Both an acrotelm and a catotelm (Ingram 1978) are present in the bog peat. The dried peat was a darker, more structured soil, with only hemic and sapric peat present. The dried peat was a shallower soil than the bog peat, 23 cm and 140 cm, respectively. A watertable was present in the bog peat but not in the dried peat. In contrast to the diplotelmic bog peat, the dried peat may be considered haplotelmic (Ingram 1978). Detailed descriptions of the chemical and physical charac-

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teristics of the bog peat and the dried peat can be found in Grover *et al.* (2005) and Grover and Baldock (2010, in press; S. P. P. Grover and J. A. Baldock, unpublished).

Sample collection

We surveyed Wellington Plain peatland extensively to choose representative locations of bog peat and dried peat to collect cores for analysis. Expert local knowledge was contributed by experienced colleagues. Ten continuous cores of peat were collected (surface to underlying mineral material), comprising four cores of bog peat and six cores of dried peat. Cores of bog peat were collected in two sections. PVC (polyvinyl chloride) pipe (8.5 cm diameter) was carefully inserted into the surface peat, to minimize compaction, and a Russian D-section corer (3.5 cm diameter) was used to collect cores from the deeper, less fibrous peat below 20 cm. The dried peat cores were sampled with a hemispherical peat corer (2.8 cm diameter). All samples were collected in the summer of 2003/2004, immediately returned to the laboratory and frozen until required for analysis. Frozen cores were sawn into slices and freeze-dried or oven-dried at 60°C.

^{14}C dating

Accelerator mass spectrometry (AMS) radiocarbon dating was carried out at the Australian Nuclear Science and Technology Organisation (ANSTO), Sydney. Ten cores of peat were prepared for radiocarbon dating, with the surface and basal sections dated. Of these, the four bog peat cores were selected for high resolution dating through the core. All new plant material growing through the dried peat was carefully removed prior to grinding. An acid-alkali-acid pretreatment removed humic and fulvic acids, leaving the fibrous fraction, which was considered most appropriate for defining when the organic materials were originally deposited. The samples underwent combustion at 900°C in sealed evacuated silica tubes in the presence of excess copper oxide, copper wire and silver wire. The resulting carbon dioxide was purified, and then reduced to graphite by heating overnight to 900°C with excess hydrogen in the presence of an iron catalyst (Hua *et al.* 2001). The $^{14}C/^{13}C$ isotopic ratio was measured on the resulting graphite/iron mix at the Australian National Tandem Research Accelerator (ANTARES) AMS facility (Fink *et al.* 2004) relative to the internationally accepted HOxI standard material (Stuiver 1983). Corrections were then applied for the preparation and spectrometer background and for the isotopic fractionation. Conventional radiocarbon ages were calculated from the corrected ratios. We used OxCal (Bronk Ramsey 1995, 2001) to transform the radiocarbon age into a probability distribution of calendar ages, and assigned a calendar age based on this probability distribution, with the dates of adjacent samples in mind. This is the common practice for developing peat core chronologies, and while it has limitations (see Blaauw & Christen 2005), it yields sufficient precision for this study. Results are presented as years before present (BP).

^{210}Pb dating

^{210}Pb dating of peat is an established technique (Appleby *et al.* 1997; Espi *et al.* 1997; Holynska *et al.* 1998; Vile *et al.* 1999), and was carried out at ANSTO, Sydney for this project. One core of each of bog peat and dried peat was selected for ^{210}Pb dating. The whole of the dried peat core, and the top 20 cm of the bog peat core, were divided into 1 cm slices. Low sample weight required some samples to be combined (i.e. more than 1 cm of peat was analysed in one sample). The analysis was completed in two batches. The excess ^{210}Pb activities (Bq kg^{-1} peat) from the first batch indicated that, in the bog peat, background levels of excess ^{210}Pb activity had not been reached by 20 cm depth. Thus, in a second batch of analyses, samples collected between 0 and 50 cm were analysed to identify the depth at which ^{210}Pb had decayed to background levels.

Excess ^{210}Pb activity was measured as total ^{210}Pb activity (measured via the granddaughter isotope ^{210}Po) minus supported ^{210}Pb activity (measured via ^{226}Ra). Ground samples of 0.5–1.5 g were spiked with ^{209}Po and ^{133}Ba yield tracers and leached with hot concentrated acids to release ^{210}Po and ^{226}Ra. ^{210}Po was autoplated onto Ag disks after reduction of Fe^{3+} with ascorbic acid. ^{226}Ra was co-precipitated with $BaSO_4$ on to a filter source. The activities of ^{209}Po, ^{210}Po and ^{226}Ra were counted with high resolution alpha spectroscopy at 4.882, 5.305 and 4.785 MeV, respectively. ^{133}Ba was measured on a gamma ray detector at the 356 keV peak. The analyses followed ANSTO's standard methodology (Seen *et al.* 2004).

^{210}Pb dating is usually applied to stratified sediments. Radioactive ^{210}Pb is deposited, from the atmosphere, on the surface and decays *in situ*. A continual build-up of sediment results in an exponential decline with depth in the activity of excess ^{210}Pb in the undisturbed sediment core. Measurements of the activity of excess ^{210}Pb with depth thus enables the creation of a model relating depth to age (Oldfield & Appleby 1984) based on the modified constant initial concentration model of Brugam (1978). This standard application of ^{210}Pb dating was used for the bog peat core.

Our application of ^{210}Pb dating to the dried peat, a disturbed sediment core, is, to our knowledge, a novel use of this technique. If dried peat formation had been initiated by livestock, it would have occurred between the 1850s, when livestock were first introduced to the area (Cabena 1980), and the 1950s, when extensive dried peats were first recorded (Costin 1952). At the current peat surface, excess ^{210}Pb activity was anticipated to be similar in the bog peat and the dried peat (as the surface of both peats is currently exposed to the atmosphere). However, the dried peat has not been accumulating material since it drained, so below the surface we anticipated an abrupt decrease in excess ^{210}Pb activity if the dried peat was actually a remnant of an original bog peat. Comparison of the subsurface ^{210}Pb activity with the model developed for the bog peat core enabled the date of drainage to be determined.

Mass balance of carbon and lead

To investigate the contributions of biological and physical loss of material in the formation of dried peat, we determined

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mass balances of carbon and lead for cores of bog peat and dried peat. In physical loss of material, both lead and carbon are lost, in equal proportions, from the peat core under the assumption that all lead is retained on surfaces of organic material. However, in biological loss of material via mineralization, carbon is lost from the peat as CO_2, but lead is retained because it binds to remnant organic materials. Determination of mass balances for carbon and lead required data on the concentrations of these two elements, and bulk density, for continuous cores of peat. Carbon contents were determined in duplicate for all samples from one core each of bog peat and dried peat with a Europa Roboprep carbon and nitrogen analyzer (Europa Scientific, Crewe, UK). Lead contents were determined on the same samples by Inductively Coupled Plasma Optical Emission Spectroscopy (ICP OES) with a Spectroflame Modular instrument (Spectro Instruments, Kleve, Germany).

Data analysis

ANOVA was used to look for differences in basal ages between bog peat and dried peat. The analysis was performed with STATISTICA 7 (Statsoft 2005).

RESULTS AND DISCUSSION

The onset and rate of peat formation

Peat appears to have begun forming at Wellington Plain just over 3000 years ago. The average age of basal peat from the bog peat cores was 3315 years BP (Fig. 4). Numerous other peat bogs in the Australian Alps also began forming at this time (Dodson 1987; Kershaw *et al*. 1997). Pollen analyses suggest that the peat-forming vegetation at Wellington Plain peatland has remained stable for several thousand years, and is the same for both bog peat and dried peat (Elwood 2001).

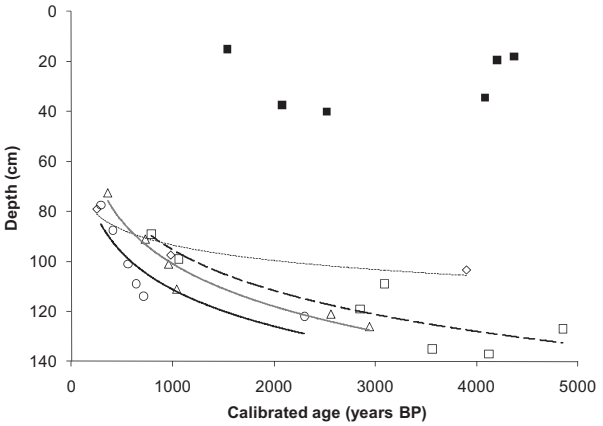

Fig. 4. Calibrated ^{14}C age *versus* depth for four cores of bog peat (open symbols) and basal samples from six cores of dried peat (filled squares). Each bog peat core is indicated by a different symbol. Logarithmic trend lines for the bog peat cores are associated with the data points of each symbol. BP, before present.

The four cores of bog peat from Wellington Plain peatland all displayed a convex age *versus* depth curve, best described by a logarithmic trend line (Fig. 4). The variation between the four cores from within the one peatland is testament to the complex nature of the bog ecosystem and the impact of the uneven underlying topography. The data in Figure 4 highlight the danger of making generalizations from one core. Outliers, such as in the square data set in Figure 4, are a common occurrence in radiocarbon chronologies (Blaauw & Christen 2005). While a logarithmic equation best fits the data, comparison with earlier work on peat accumulation in Australian bogs requires simplification to a linear model. This yields an average peat accumulation rate of 0.04 ± 0.01 cm per year, within the range of results found by Dodson (1987) and general values for Australian bogs quoted by Hope (2003). Blaauw and Christen (2005) suggest that, globally, bogs accumulate at 0.05 ± 0.025 cm per year, and our results also fall within this range.

Peat accumulation is a slow, non-linear process, which is best understood within the context of bog growth. Models of peat bog growth, building on the seminal ideas of Clymo (1978, 1984), have conceptually and mathematically developed our understanding of how bogs function (Belyea & Warner 1996; Wieder 2001; Yu *et al*. 2001). Central to all these models is the idea that sediment in a growing peat bog is not static, but rather undergoing a continual process of addition (new plant material is added at the surface), compression (material is compacted by the ever-increasing mass of peat above) and subtraction (material is removed via decomposition and possibly erosion). This is reflected in the superior fit of a logarithmic equation over a linear equation to age by depth relationship (Fig. 4). Indeed, 'the majority of published peat profiles show concave peat age–depth curves, suggesting that decay in deep peat is an ongoing process' (Yu *et al*. 2001).

The parent material of dried peat

Dried peat and bog peat appear to have begun forming at the same time. The average ages of peat from the base of the bog peat cores and dried peat cores were 3315 and 3323 years BP, respectively (Fig. 4). There was no significant difference ($P = 0.99$) between calibrated ^{14}C ages from the base of four bog peat cores and six dried peat cores. As in the bog peat, the range of basal ages reflected the complexity of the peatland and the variation in topography of the substratum

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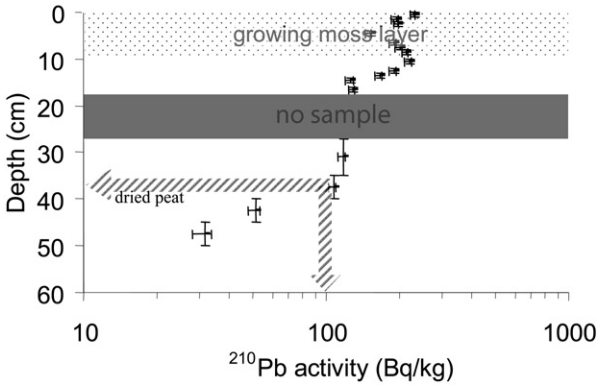

Fig. 5. Depth *versus* activity of excess ^{210}Pb for the bog peat. Note the *x*-axis is on a log scale. The *y* error bars indicate the depth of the sample and the *x* error bars are ± the error associated with each measurement. The upper stippled layer is the 'growing moss layer', analogous to the 'mixed surface layer' seen in cores of lake sediment. The striped arrows indicate the excess ^{210}Pb activity of the dried peat, and the equivalent depth in the bog peat.

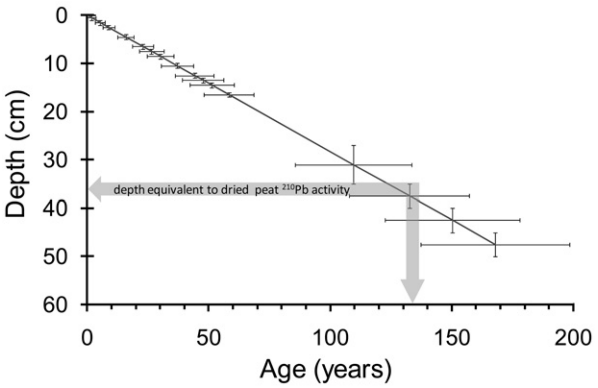

Fig. 6. Model of age *versus* depth derived from ^{210}Pb results for the bog peat. The bog peat depth equivalent to the excess ^{210}Pb activity of the dried peat, and the corresponding age, are indicated by the grey arrows.

beneath the peat. The surface of the dried peat was less than 200 years old and thus could not be dated with ^{14}C.

The timing of the change from bog peat to dried peat

The bog peat is a growing entity, and thus the core could be dated using the traditional constant initial concentration methodology (Brugam 1978; Oldfield & Appleby 1984). The excess ^{210}Pb activity for the bog peat core is shown in Figure 5. These results enabled calculation of an accumulation rate of 0.25 cm per year below 10 cm. Above 10 cm depth, excess ^{210}Pb activity did not decrease exponentially, likely due to mixing in the continually growing moss layer, analogous to the mixed surface layer often seen in lake sediment ^{210}Pb cores (Oldfield & Appleby 1984). Belyea and Warner (1994) suggest that incoming lead may fall through the open structure of the living moss at the bog surface before binding to cation exchange sites on the more decomposed material below. The open structure of this growing moss layer yielded a higher accumulation rate, of 0.32 cm per year, resulting in a two-part model of peat bog growth, shown in Figure 6. The down-core increase in ^{210}Pb activity at 17 cm depth could be caused by the influx of material with a different initial ^{210}Pb activity (Harle *et al.* 2002).

The model in Figure 6 suggests that 15 cm of peat has accumulated in the past 50 years, and 27 cm in the past 100 years. These results are well within the range of growth rates for ^{210}Pb-dated bogs presented by Turetsky *et al.* (2000).

Table 1. Activity of excess ^{210}Pb in the dried peat

ANSTO code	Depth (cm)	Activity of excess ^{210}Pb (Bq kg^{-1})
H490	0–2	323 (8)
H958	2–3	192 (5)
H959	4–5	**97 (3)**
H491	6–8	57 (3)
H960	9–10	29 (2)
H492	12–14	27 (1)
H961	14–15	23 (1)
H962	15–16	25 (2)

Associated errors are in brackets. ANSTO, Australian Nuclear Science and Technology Organisation.

As the dried peat was no longer accumulating, we employed a novel application of the ^{210}Pb methodology, which centres around comparison of a disturbed core (the dried peat) with an intact, accumulating core (the bog peat). The surface of the dried peat had a higher ^{210}Pb activity than did the surface of the bog peat (323 cf. 227 Bq kg^{-1}, Table 1 and Fig. 5). This build-up of lead on the dried peat surface suggests that attrition of the dried peat is occurring more slowly than the bog peat is growing. At 2–3 cm depth, the activity of excess ^{210}Pb in the dried peat was comparable with that in the bog peat at the same depth. Below 3 cm, the ^{210}Pb activity declined rapidly in the dried peat, reaching background levels by 9 cm depth. It is the dried peat sample from 4 to 5 cm depth (bold in Table 1) with ^{210}Pb activity lower than that at comparable depth in the bog, but above background levels, that holds the key to when the dried peat was originally drained.

The ^{210}Pb activity of the dried peat at 4–5 cm (97 Bq kg^{-1}) fits into the ^{210}Pb activities of the bog peat core just below 35 cm (Fig. 5, 105 Bq kg^{-1}). The

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Table 2. Mass balances of carbon and lead for one core each of bog peat and dried peat

Peat type	C (g m^{-2})	Pb (g m^{-2})	C/Pb
Bog peat	49 671	96	515
Dried peat	28 933	26	1099

growth model developed for the bog peat (Fig. 6) suggests that the dried peat below 3 cm depth was thus 131–139 years old. This peat was likely at the surface some time between 1865 and 1873. Cattle were first taken to Wellington Plains in 1855 (Cabena 1980), and thus peat attrition seems to have occurred shortly after grazing began. These ^{210}Pb results suggest that the drainage of bog peat to form dried peat at Wellington Plain coincided with the introduction of livestock to the area.

The mode of the change from bog peat to dried peat

Dried peat could have formed by: (i) physical loss of material, where whole peat including carbon and lead leaves the system; (ii) biological loss of material, where rapid aerobic decomposition (microbial respiration) removes carbon and oxygen but leaves lead in the remaining peat; or (iii) by a combination of physical and biological processes. The ratio of carbon to lead in the dried peat is greater than in the bog peat, which suggests biological loss of material was not dominant, but rather physical loss of material is likely to have been the main process (Table 2). However, these results are from only one core each of bog peat and dried peat, and thus further data are required to substantiate the proposition that dried peat formed primarily by a physical loss of material from a drained bog peat.

CONCLUSIONS

The results obtained have allowed assessment of the rate of peat formation, whether or not bog peat is the parent material of dried peat, and how and when dried peat formed. The peatland at Wellington Plain, Victoria, Australia began forming about 3300 years ago and has been accumulating at about 0.04 ± 0.01 cm per year. The radioisotope results support the hypothesis that bog peat is the parent material of dried peat. Dried peat formation at Wellington Plain appears to have begun about 131–139 years ago, coincident with the introduction of cattle grazing to this area. The mass balance data provide initial support for the proposition that physical loss of peat was the dominant process of dried peat formation. Overall, our results suggest an anthropogenic cause for dried peat formation, and thus lend support to the active rehabilitation of dried peat areas in the Australian Alps. The ability of these soils to store and further sequester carbon will be enhanced by measures to raise the watertable where drainage lines have been entrenched by trampling. Our novel application of the ^{210}Pb dating technique holds potential for improving our understanding of the recent history of other partially disturbed ecosystems.

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