An insect derived peat? The curious case of sediments at Bogong moth aestivation sites

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SUMMARY

The Bogong moth *Agrotis infusa* (Boisduval) is a migratory noctuid moth from south-eastern Australia which annually migrates thousands of kilometres for a period of aestivation in boulder-piles, caves and crevices on the highest mountain peaks of the Australian Alps. The same aestivation sites are used each year, and over time a highly organic deposit made predominately of preserved insect chiton and plant matter has accumulated at many of them. Examples of these sediments were characterised using a range of standard methods to ascertain the organic content, the carbon and nitrogen components, the lipids (oils and waxes) concentration and the acidity of each deposit. The deposits were found to be high in organic matter with a relatively high C:N ratio, low in lipids, and highly acidic. The acidity and amount of organic matter in these deposits are above threshold levels for classification as peat. The high concentration of insect remains, their taphonomic importance and the ecological context warrant the naming of sediments at Bogong moth aestivation sites as "insect derived peat" or "moth peat".

KEY WORDS: *Agrotis infusa*, Australian Alps, cave peat, moth peat

INTRODUCTION

The Bogong moth *Agrotis infusa* (Boisduval) is a well-studied insect distributed in the southern half of the Australian continent (Common 1954, Green 2008, Warrant *et al.* 2016, Mansergh & Heinze 2019, Green *et al.* 2021). *A. infusa* is a noctuid moth which feeds on broadleaf pasture plants, and each spring this species migrates thousands of kilometres from breeding grounds in inland eastern Australia west of the Great Dividing Range, for a period of summer hibernation (aestivation) in caves and crevices amongst rocks on the highest mountain peaks of the Australian Alps. The Bogong caves are culturally and ecologically significant. A number of endemic and rare species utilise these aestivation sites, including two obligate nematode species living in the sediments, a species of springtail (*Triachanthella* sp.), which is a fungus feeder, as well as the endangered mountain pygmy-possum. All current aestivation sites are located in national parks. At the aestivation sites, densities of individual moths may reach several thousand per square metre of rock wall and substantial peaty deposits often develop on the ground beneath them (Figure 1). Most of these deposits have been found to be less than 1000 years old (Keaney 2016). Sampling of these deposits has shown that they are composed of a mixture of rock parent material with a diversity of organic material including seed capsules, leaves, twigs, beetle elytra, moth hamuli, mammalian hair and bird feathers, with microscopic examination revealing that the organic fraction is composed of strikingly large amounts of chitinous material from insects (wing and skeletal remains, mainly of Bogong moth), along with plant detritus at various stages of humification and fungal remains.

Our research aims to establish the physical and chemical makeup of the peaty deposits present in caves and crevices at Bogong moth aestivation sites, in order to better understand the preservative qualities of this unique terrestrial sediment as well as to ascertain the importance of the presence of Bogong moth remains for organic preservation in this palaeo-environmental archive. Here we investigate the composition of the cave deposits, and especially the features that characterise them and confer on them important peat-like preservation qualities, such as the large amount of moth remains, high organic matter content and acidic nature.

METHODS

Study sites

The study sites were located on mountain peaks in granitic geology in the northern section of the Australian Alps, where in summer aestivating

Figure 1. Above: aestivating Bogong moths (*Agrotis infusa*). Below left: peaty deposit in a crevice between rocks (at Bogong Peaks). Below right: Surface of a peaty deposit (at Gingera Big Cave) showing remains of *A. infusa*, leaves of the mountain plum-pine *Podocarpus lawrencei*, lichen filaments and twigs.

Bogong moths can be found hiding in complex boulder piles, scree-slopes, rock-shelters and caves (Figure 2).

Sampling

Fifteen cores from eight different sites were taken. Prior to sampling, probing of sediments using a thin metal rod was undertaken to locate the deepest sediments. The deepest section of each peaty deposit was sampled using a modified 30 cm lightweight plastic piston-corer (Figure 3). The corer was designed to be compact, enabling sampling in limited spaces, and incorporated a piston for improved retrieval and ability to extrude the core. Soft profiles deeper than 30 cm were cored using 25 mm diameter PVC extension rods. Gingera Big Cave had deeper and denser sediments that were not in a confined space and could be sampled by hammering a 90 mm diameter PVC pipe into the sediments using a wooden mallet.

Analyses

Analysis of sediments was undertaken in the laboratory at the Department of Archaeology and

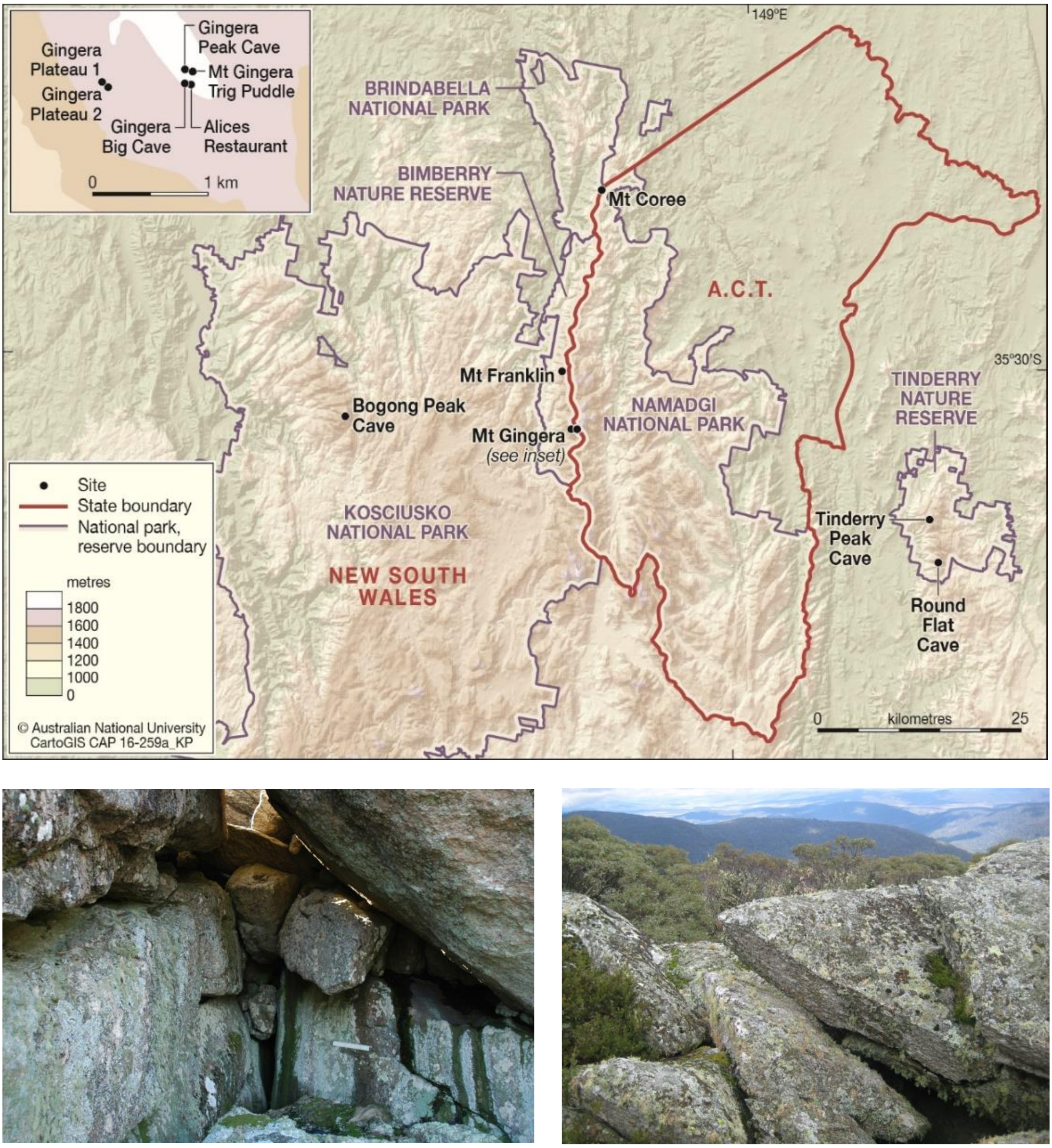

Figure 2. Above: map of the northern part of the Australian Alps showing the locations of study sites. Below: two of the boulder-pile study sites, at Bogong Peaks (left; note the 50 cm section of PVC tubing for scale) and on Mount Gingera (right).

Natural History at the Australian National University. Sediments were stored in a refrigerator at 4 °C, for a maximum of six months while fieldwork was carried out. Acidity was measured each centimetre along the cores using a distilled water solution and an Oakton pH700 pH/mV/°C/°F meter. The cores were both bulk sampled and fractionated for insight into differences of sediment grain sizes. This proved to be a quick and effective sampling method, allowing a general inter-site comparison of organic content. Bulk samples were weighed, dried at 110 °C for 24 hours and re-weighed to determine percentage moisture loss. To measure organic content as Loss on Ignition (LOI), samples were placed in tared ceramic boat crucibles, air dried in a Labec Incubator at 80 °C for 72 hours, then pyrolysed

Figure 3. Corer used for sampling smaller and softer aestivation site deposits.

at 550 °C for three hours using a Walter Oakes Instrument Co. 0–1100°, Model No. F54B ashing furnace. Since both the peaty samples and the granodiorite parent rock were acidic, all losses were interpreted as being due to organic matter alone and not calcinable material (bicarbonate or carbonate). To obtain fractionated samples the material was dispersed with 5 % sodium hexametaphosphate (Calgon) for 24 hours then separated into four broad size classes using agitated 150, 250 and 355 µm screening. The fractionated samples were analysed for LOI as for the bulk samples. Carbon and nitrogen content of all samples was determined using an Elementar Vario Max CNS Autoanalyser. The C:N ratio was evaluated as the quotient of % C and % N (C/N). The lipids content in bulk cave sediment samples and dried moth samples collected in Canberra were determined by rinsing repeatedly with diethyl ether, evaporating the filtered extract and then weighing the extract. Moths were collected in Canberra to minimise impact at aestivation sites.

RESULTS

The peaty deposits at aestivation sites cover the cave floor and are shallow (< 60 cm). They are generally homogeneous in appearance, with no obvious changes in the profile below the top 3 cm (Figure 4). Greatest development is usually directly on flat granite rocks and regolith, or in depressions, in areas of higher water flow below granite rock faces which are seasonally covered by large clusters of moths, some of which die and are accumulated on the cave floor by water movement.

Parallel records of total organic carbon for bulk samples and size fractions from ten sites are shown in Table 1, while the data for C and N content, lipids (oils and waxes) content and pH are shown in Table 2.

DISCUSSION

Four sites (G4, BP1, BP2, GBC1) showed lower C/N values than the others. We suggest that this reflects high nitrogen input from large amounts of insect chiton originating from *A. infusa*. This hypothesis is supported by the data for fractionated samples at the bottom of Table 2, which shows that the larger more robust fragments, such as woody litter, had higher C/N values than smaller fragments. The variability in organic content between sites reflected a range of preservative properties, with differences in site characteristics - such as open versus enclosed situations - playing an important role. Different size classes were also differentially represented. Trends in carbon content were similar between LOI (%) and C/N analyses, although LOI (%) indicated more than twice the carbon in samples from enclosed sites (BP1, BP2, AR2 and G4) compared to C/N analysis.

There were substantial differences in moisture and organic carbon contents between open and enclosed sites. It appeared that the nature of site shelter affected deposit moisture, with overhang type shelters being much less moist than other sites. Overhang sites also had the least organic matter,

Figure 4. Bogong Peaks (BP2) core, illustrating the homogeneous nature of the sediment.

Table 1. Moisture and organic matter contents (as LOI, dry weight basis) of bulk and fractionated aestivation site deposits. Moisture loss was calculated on the basis of drying bulk samples at 110 °C; LOI=loss on ignition.

Site	Site code	Profile depth (mm)	Moisture loss (%)	LOI (%)				
				bulk sample	size fraction (µm)			
					0–125	125–250	250–355	>355
Gingera Cave 4	G4	340	30.1	24.7	96.6	40.5	31.8	19.9
Alices Restaurant 2	AR2	320	42.4	38.7	53.7	40.9	30.7	17.3
Alices Restaurant 4	AR4	170	34.4	29.4	80.7	35.2	21.4	18.5
Gingera Big Cave 1	GBC1	580	54.2	43.2	88.7	58.8	56.4	32.0
Gingera Overhang 2	GP2	300	12.3	14.4	42.1	18.4	15.9	6.2
Bohong Peaks 1	BP1	180	50.0	36.7	-	44.7	41.1	38.4
Bohong Peaks 2	BP2	270	55.5	42.7	-	45.8	49.1	26.4
Round Flat Cave 1	RFC1	180	14.6	12.7	34.4	11.5	7.2	2.7
Round Flat Cave 2	RFC2	180	5.0	13.0	9.1	9.1	8.4	4.4
Round Flat Cave 3	RFC3	110	12.2	15.7	9.4	9.4	4.2	2.2

indicating that soil moisture is important for organic preservation. Thus, the deposits from simple rock overhang sites (Round Flat Cave and Gingera Plateau Overhang) were less organic and drier than those from other sites, possibly because of their greater exposure to desiccating westerly summer winds. The conditions of greater saturation (deposits permanently moist) found at the top of Mount Gingera (Gingera Cave, Alice's restaurant, Gingera Big Cave) and at Bogong Peaks, where the sites were both enclosed/cave sites and in an area with high rainfall, were more favourable for the preservation of organic remains.

The organic content of bulk samples from deposits found in enclosed/cave sites ranged from 24.7 % at Gingera Cave to 43.2 % at Gingera Big Cave, placing these deposits above the 20–30 % lower thresholds for classification as peat provided by the International Peatland Society (IPS 2021). The organic content of different size fractions varied, with the smallest fraction being the most organic and the largest fraction the least. The Bogong Peaks >125 µm fraction could not be measured accurately because its organic content approached 100 %, meaning there was no measurable residue after ashing. All sites were much more organic in the smaller size fractions, apart from the highly organic Bogong Peaks 2 site.

Peat has been defined broadly as accumulated dead plant material that has remained incompletely decomposed due to a lack of oxygen, that forms in a

Table 2. Carbon (C), nitrogen (N) and lipid contents (dry weight basis) plus acidity (pH) for peat profiles at aestivation sites. SD = standard deviation, n = number of observations.

Site	Site code	Organic C (%)	Organic N (%)	C/N	Lipids (%)	pH (± SD)	
						Value	n
Gingera Cave 2	G2	-	-	-	-	4.3 ± 0.2	17
Gingera Cave 3	G3	-	-	-	-	4.2 ± 0.3	25
Gingera Cave 4	G4	11.10	1.67	6.7	0.054	3.8 ± 0.2	32
Alices Restaurant 2	AR2	15.20	1.13	13.4	0.130	4.0 ± 0.1	32
Alices Restaurant 4	AR4	18.91	1.26	15.1	0.170	3.9 ± 0.2	17
Gingera Big Cave 1	GBC1	23.33	2.30	10.2	0.087	4.0 ± 0.3	58
Gingera Overhang 2	GP2	10.40	0.51	20.4	0.026	3.7 ± 0.1	30
Bogong Peaks 1	BP1	10.98	1.91	5.7	0.049	4.2 ± 0.2	18
Bogong Peaks 2	BP2	18.09	3.21	5.6	0.047	4.1 ± 0.1	27
Bogong Peaks 3	BP3	-	-	-	-	3.8 ± 0.1	13
Round Flat Cave 1	RFC1	7.70	0.45	17.2	0.075	3.9 ± 0.2	18
Round Flat Cave 2	RFC2	6.80	0.40	17.2	0.041	3.7 ± 0.1	18
Round Flat Cave 3	RFC3	8.71	0.52	16.7	0.064	3.8 ± 0.1	11
Tinderry Peak Cave 2	TP2	-	-	-	-	4.1 ± 0.1	30
Tinderry Peak Cave 4	TP4	-	-	-	-	3.8 ± 0.1	5
Average C and N composition (± SD)	Bulk samples	13.1 ± 5.6	1.3 ± 1.0	12.8 ± 5.6			
	Size fractions ≥125 µm	13.2 ± 9.6	1.5 ± 1.3	15.6 ± 9.6			
	Size fractions ≥250 µm	12.1 ± 7.4	1.4 ± 1.4	17.7 ± 13.2			
	Size fractions ≥355 µm	7.2 ± 5.2	0.83 ± 0.99	30.0 ± 26.8			

waterlogged environment which is typically acidic (Abercrombie *et al*. 1978); and in a more explanatory way as decayed plant organic materials that accumulate in environments where conditions preclude the ability of microorganisms to completely recycle the plant substances (Stout & Spackman 2002). On the other hand, Moore & Belamy (1974) contextualised peat in terms of energy, seeing it as a stored surplus of energy resulting from low levels of decomposer activity. The common trait of peat deposits is that they develop where the accumulated remains of biological communities exceed the capacity of the environment to destroy or recycle those materials (Rich 2015). Since there is a diversity of peat deposit types it is difficult to base a sedimentary classification solely on a single physical characteristic such as organic matter content. While the organic matter content of the sediments is a useful classificatory trait, and the deposits at enclosed Bogong moth aestivation sites are highly organic, insights into formation processes are also helpful.

Bogong moth aestivation sites mimic the conditions for peat formation to produce sediments with significant preservation of plant material in a matrix dominated by insect remains. Our research on the taphonomy of sediments that accumulate at Bogong moth aestivation sites has shown that the deposits are acidic and highly organic, with variable total nitrogen and C/N values and a small lipids component.

There is a distinct taphonomic and depositional difference between the small and discrete aestivation site deposits and the nearby grassland, heathland and woodland soils studied by Huber *et al.* (2010), which are more continuously distributed in the landscape. Typical sedimentary deposits from peatlands in south-eastern Australia have C/N values for dried peat of 36.5 (Grover *et al*. 2005). Thus, the sediments accumulating at aestivation sites might have much higher C/N values if they were traditional vegetation derived peats accumulating under anaerobic conditions without a seasonal input of insect chiton. However, while *Sphagnum* peatlands occur < 1km from the aestivation sites, these are located at lower altitudes and on flatter terrain than the mountain tops used by *A. infusa*.

Site selection for aestivation by the moth favours locations with high precipitation and low temperatures associated with altitude (Common 1954). The environment of the caves and crevices which are sheltered and moist, often with some groundwater emergence, are quite incidentally also intrinsically good environments for organic preservation. Year-round groundwater emergence provides a ready source of hydration for the moths, as well as saturating the deposit to create a stable preservative environment. Water is also a major agent in carrying detritus from the aestivating moths into areas with lower gradient or water pooling where sediments tend to accumulate. High-gradient microtopography below the aestivation site acts to disperse sediments and is prone to erosive episodes. Larger aestivation sites may have areas of both sediment accumulation and erosion.

Moth remains have a low wet-strength, and when saturated have a tendency to stick to underlaying surfaces. It is the exclusion of air, high moisture content and the acidity of the deposits that minimises microbial activity. While the concentrations of lipids in moth remains is high (18.5 %), the concentrations are much reduced in the sediments, as the volatility of these compounds limits their ability to persist for extended periods. On the basis of the range in lipids values for the different sites (0.041–0.17 %) and the moist character of the deposits with highest organic content (moisture content 30.1–55.5 %), it seems unlikely that the hydrophobic properties of oils and waxes contribute significantly to the preservation of organic matter at aestivation sites.

The deposits were generally very acidic (pH 3.3–4.9), and while there was some variability in pH between sites, with open sites being more acidic, the intra-site variability in pH was low overall. The acidity of deposits would result in poor preservation of bones and teeth but is remarkably good for proteins including pollen and hair. Moth sediments are generally both moist and acidic, and it seems that these two factors contribute significantly to the preservation of pollen and hair at all of the sheltered sites.

Bogong moths comprise a large component of the peaty deposits at their aestivation sites and their influence in promoting preservation of pollen, hair, charcoal and other potentially useful records of past environmental conditions warrants special consideration (Keaney 2016). Taking the approach of Moore & Bellamy (1974), who describe peat-producing landscapes as “unbalanced systems in which the rate of production of organic material by living organisms exceeds the rate at which these compounds are respired and degraded”, the rate of energy transfer from the breeding grounds of this migratory insect to the sediment found at aestivation sites clearly exceeds the rate of decomposition, and the sediment can therefore be termed a peat. Since peat is generally classified according to the predominant peat-forming plant (Inisheva 2006), and in the case of deposits at Bogong moth aestivation sites the predominant peat forming organism is the Bogong moth, we propose that these organic sediments could be named “insect derived peat” or “moth peat”.

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AUTHOR CONTRIBUTIONS

BK wrote the draft, analysed the data and conducted the study with AW, who carried out the laboratory work. BK and AW revised the final version of the manuscript.

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