The evolution of a coastal peatland at Byron Bay, Australia: Multi-proxy evidence from the microfossil record

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Introduction

Peatlands are highly valuable ecosystems for their ecological functions as well as their economic and societal values (Charman 2002). Yet they are also highly vulnerable to degradation by a range of anthropogenic activities and climate change (Charman 2002; Gorham and Rochefort 2003; O'Connell 2003; Rochefort et al. 2003; Vasander et al. 2003). In Australia, peatlands are an unusual and infrequent component of the landscape (Whinam et al. 2003), mostly distributed in the alpine areas of the southeast of the continent (Clarke and Martin 1999). However, areas of peat also occur in the coastal lowlands, often in dune swales, both on the east coast of Australia and on the southwest coast of Western Australia (Whinam et al. 2003). Coastal peatlands are unique environments and can be very informative about environmental and sea-level change in the coastal zone. Peat deposits in coastal areas of the Northern Hemisphere have provided informative records of water-level changes, which in turn can be used to complement existing palaeoclimatic and sea-level reconstructions (e.g. Eronen et al. 1987; Denys 1989; Campeau et al. 2000; Finkelstein and Davis 2005). At present, there is a lack of research focusing on Australian coastal peatlands. A deeper

understanding of the response of coastal areas to climatic and anthropogenic influences is required to maximise conservation efforts of these unique environments.

Coastal peat formation is induced by waterlogging of silted-up areas when there is sufficient supply of freshwater (Kumano et al. 1990). In eastern Australia, many coastal peatlands occur naturally as thin strips behind the barrier dune systems. Australian coastal peatlands are dominated by Restionaceae, Cyperaceae and Epacridaceae vegetation (Whinan et al. 2003). They were generally formed in the past 4000 to 6000 years, since the last high-sea-level stand (Lewis et al. 2008). However, they have been heavily impacted by anthropogenic activities in the densely populated, resource-rich, coastal zone (Taffs et al. 2006). As a result, many coastal peatlands have been extensively damaged and/or removed by agriculture and urbanisation land uses.

Peatland conservation in Australia is very ad hoc and mostly aims to conserve representative portions of different peatland types (Whinan et al. 2003). Yet coastal peatlands are under-represented compared with other peatland types because of their location within the densely populated coastal zone. Developing a full understanding of the pre-anthropogenic impacts and natural variability of coastal peatlands is required to improve their management and conservation. Palaeoecological techniques provide ideal tools to identify natural benchmark conditions and variability such as vegetational change and response to anthropogenic impacts (Gaiser and Ruhland 2010). This provides essential information for managers of peatland systems to maximise their conservation.

Plant macrofossils such as phytoliths (e.g. Lewis 1981; Piperno 1988; Carter 1998; Kealhofer and Penny 1998; Parr 2003; Taffs et al. 2006) and pollen (e.g. von Post 1916; Godwin 1940; Wein et al. 1987; Gignac et al. 1991; Jasinski et al. 1998) are the traditionally used microfossils in peatland palaeoecological studies. They provide important information on vegetation composition and change over time. Phytoliths and pollen complement each other in a number of ways. Firstly, due to its airborne nature, pollen provides an indicator of regional vegetation changes, while phytoliths are for the most part deposited in situ and are useful for examining changes in vegetation at a specific site. Secondly, not all plants are prolific producers of phytoliths and/or pollen, and thus using both of these microfossils for palaeoecological reconstruction provides the best opportunity to identify a broad range of vegetation types (Kealhofer and Penny 1998; Taffs et al. 2006).

In coastal peatlands, the changing interface between the marine and terrestrial landscape strongly influences peatland water levels and water quality (Freund et al. 2004). Diatoms are regarded as very sensitive indicators of changes in water quality (Stoermer and Smol 1999) and are useful tools to describe palaeoenvironmental conditions in humiferous as well as in clastic lithofacies, such as those that accumulate in coastal lagoons. However, comprehensive studies of diatom flora from peatland systems remain scarce (Pienitz 2001; Gaiser and Ruhland 2010).

While peats are useful archives of environmental information, they are difficult environments in which to study siliceous microfossils such as diatoms and phytoliths (Bennett et al. 1991). Biogenic silica cycling causes breakdown of siliceous materials in anoxic, organic-rich, neutral-pH environments that are typical of coastal peatlands (Bennett et al. 1991). The fragility of diatom frustules makes them particularly susceptible to degradation and breakdown. Yet diatom dissolution data can aid interpretation of sedimentary profiles as records of limnological, ecological and environmental change (Ryves et al. 2009).

There are some coastal peatland sites that have sufficiently well-preserved siliceous microfossils to identify environmental change. These include the Beaufort Sea (Campeau et al. 2000), the western Belgian coast (Denys 1989), the western coastline of the United States and Canada (Eronen et al. 1987), the Lower Saxony, Germany (Freund et al. 2004), and the coastal plains of Japan (Kumano et al. 1990). In some of these studies, diatom dissolution

occurred to the extent that full counts of each sample could not always be obtained (Eronen et al. 1987; Denys 1989; Campeau et al. 2000). Yet the extent of dissolution or fragmentation was used to aid environmental interpretation.

Given the strengths and weaknesses of any given environmental indicator on its own, the advantages of using multiple proxy indicators have been underscored in numerous peatland palaeoecological papers (e.g. Korhola 1990; Jaskinski et al. 1998; Rühland et al. 2000, 2006; Langdon et al. 2003; Blundell and Barber 2005; Myers-Smith et al. 2008). The aim of this paper is to examine the preservation of siliceous microfossils (diatoms and phytoliths) in a coastal peatland in eastern Australia and determine the environmental history that these fossils are able to reveal in combination with pollen, lithological and chronological information. A more detailed understanding of the evolution of this coastal plain and the response of the ecosystem to anthropogenic impacts is a priority to inform management strategies for the region's coastal peatlands.

Study area

Byron Bay (Figure 1) is located on the northern coast of New South Wales, Australia. It is a quartz-dominated sand province that has had its geomorphology shaped by pre-Holocene estuarine sediment deposits, the onshore movement of sands which accompanied the Holocene sea-level rise, and the reworking of coastal deposits by wind, wave and current actions after sea levels stabilised around 6000 yr BP (Chapman et al. 1982). The adjacent Belongil estuary has developed as a result of tidal forces in the relatively short time available during the Holocene for the estuary to infill under a steady sea level (Harris et al. 2002).

Figure 1. Location of Byron Bay: (a) location of Byron Bay within New South Wales, Australia; (b) photo of the site where the sediment core was extracted; (c) location of the sediment core extraction site

The site used for this study is 2.6 m asl (Byron Shire Council 2003). It is a 24 ha wetland located in the Belongil Swamp, which is a back barrier swamp on an estuarine/alluvial plain, bordered by bedrock hills to the west, and by a series of up to 13 Pleistocene beach ridges with an elevation of 5–6 m to the east (Geomarine 1997). The swamp is connected to an intermittently open estuary, Belongil Creek, via artificial drains. The Belongil Creek catchment drains an area of approximately 2840 ha (Geomarine 1997). The wetland is dominated by peat, and is bordered with *Melaleuca quinquinervia* and *Blechnum indicum* dominated vegetation. The surrounding area also contains significant proportions of dry sclerophyll, sedgeland and littoral rainforest associations.

Methods

In 2003, three sediment cores were extracted along a transect that incorporated the major depositional environments of a coastal peatland complex near Byron Bay (28° 38' 00" S, 135° 34' 25" E). We present here the results of analysis of a 5.2 m long sediment core retrieved in 1.5 m sections using a Vibracorer. Results of the two smaller sediment cores were reported in Taffs et al. (2006). The sediment-core sections were split vertically, with one half frozen for lithological analyses (sediment grain size, loss on ignition and pyrite content) and the other half sub-sampled for microfossil analysis (pollen, phytoliths and diatoms). In addition, pollen was extracted from sediment samples for AMS ¹⁴C analysis using the analytical facilities of the Australian Nuclear Science and Technology Organisation (ANSTO).

Organic content was determined according to the loss-on-ignition method of Bengtsson and Enell (1986) to characterise the sediment. Samples were oven-dried then ignited in a muffle furnace at 550°C for two hours. After cooling within a dessicator, samples were weighed and the lost material expressed as a percentage of dry weight.

The reduced inorganic sulfur fraction (which includes pyrite and other iron disulfides, elemental sulfur, and acid volatile sulfides) was measured in duplicate on 20 samples using the chromium reducible sulfur technique of Sullivan et al. (2000) in order to provide a measure of pyrite content of the sediments. After peroxide oxidation, all residues were washed three times with distilled water, centrifuged, and oven-dried at 60°C before chromium reducible sulfur analysis. Pyrite can indicate the prevalence of a reducing environment occurring under anoxic conditions during deposition (Bajpai et al. 2001). Thus, the occurrence of pyrite in sedimentary sequences indicates marine origins and can have significant palaeoenvironmental value.

Diatom samples were processed according to the method of Parr et al. (2004), and were inspected under an Olympus CX40 compound light microscope fitted with an Olympus DP10 digital camera at 1000X magnification. A minimum of 300 diatom frustules were identified and counted from each sample to determine the diatom assemblage where possible. The diatoms were identified using the photographs of Foged (1978) and Gell et al. (1999). Only species that had a relative abundance greater than 2% were included in the data set. For rapid assessment of diatom preservation, the method of Dong et al. (2008) was adopted. This method estimates diatom preservation in three categories: (1) slides with good diatom preservation (the assemblages are almost pristine with the whole community preserved well without signs of dissolution and fragmentation); (2) medium fragmentation (assemblages partially dissolved but with most species well preserved); and (3) poor preservation (most species dissolved, only robust species remaining).

Phytoliths were extracted from sediment using the method of Parr (2002). Phytoliths extracted from each sample were weighed, mounted on to microscope slides and scanned at 400x magnification on an Olympus BH2 microscope. A total of 150 diagnostic phytolith types were counted for each slide. A collection of plant species was made in and around the study site and phytoliths extracted using the method of Parr et al. (2001) for use in a comparative

database. Identification of phytoliths was based on a probability method (Parr 2004), in which fossil phytolith morphotypes were compared with those represented in a regionally specific phytolith database; the more commonly a plant taxon is represented by different morphotypes, the more likely it is considered that the taxon in the database is represented.

Pollen was extracted from 1 cu. cm of sediment using the method described in Cotter and Boyd (1998), excluding the hydrofluoric acid treatment that was considered unnecessary due to the low silica content of the sediment. Pollen extracted from each sample was mounted on to microscope slides and scanned at 600x and 1000x magnification on an Olympus BH2 microscope. A total pollen sum of 500 grains was counted per sample.

Ten samples were prepared for AMS ^{14}C dating using the pollen fraction. These were processed and measured at the Australian Nuclear Science and Technology Organisation (ANSTO, sample numbers OZH042 to OZH051, Fink et al. 2004). Radiocarbon dates were calibrated using CALIB 5.0 (Stuiver and Reimer 1993). Dates less than 11 ka were calibrated using the Southern Hemisphere radiocarbon calibration data set ShCal04 (McCormac et al. 2004). Dates 11–26 ka were calibrated using the international radiocarbon calibration data set IntCal04 (Reimer et al. 2004), while dates older than 26 ka are uncalibrated (Reimer et al. 2004).

All results were graphed using the package C2 (Juggins 2004) and displayed using a stratigraphic diagram. Biostratigraphic zones were established, based on the distinct lithological sequence observed in the sediment core.

Results

Chronology

Table 1 shows the AMS ^{14}C results with radiocarbon and calibrated ages. Radiocarbon ages ranged from 4300 ± 50 at 50–55 cm depth to $41,800 \pm 1200$ at 510–515 cm depth. Figure 2 shows the age-depth model for the sediment core and the core lithology. The basal material is fine, muddy sand, extending from 520 cm to 300 cm and corresponds to an uncalibrated radiocarbon age of $\sim 42,000$ yr BP to $\sim 33,000$ yr BP. A sand layer was deposited $\sim 33,000$ yr BP, which grades back into sandy mud from 260 cm to 130 cm, or $\sim 33,000$ yr BP to 9000–9396 cal. yr BP. There is a small horizon representing a distinct colour change at 170–175 cm, that is 10,309–10,763 cal. yr BP. The Sandy Mud and Muddy Sand sediments are typical of Pleistocene estuarine deposits on the north-coast coastal plain (McGrath and Boyd 1998; Taffs et al. 2008). The upper peat deposit is 130 cm deep and extends from approximately 5327–5709 cal. yr BP to the present.

Table 1. Radiocarbon ages from the Byron Bay sediment core

Laboratory No. ^a	Core depth (cm)	Radiocarbon age (yr BP)	Calibrated age (cal yr BP) ^b	Dated material
OZH042	50–55	4300±50	4581–4959	pollen
OZH043	120–125	4880±60	5327–5709	pollen
OZH044	140–145	8240±60	9000–9396	pollen
OZH045	160–165	9430±60	10304–10763	pollen
OZH046	170–175	15,110±110	18062–18713	pollen
OZH047	190–195	15,480±100	18647–18936	pollen
OZH048	250–255	33,530±320		pollen
OZH049	310–315	33,050±300		pollen
OZH050	410–415	42,900±1600		pollen
OZH051	510–515	41,800±1200		pollen

a. Australian Nuclear Science and Technology Organisation (ANSTO) laboratory code.

b. Calibrated using program CALIB 5.0, reported using the 2 sigma range.

Figure 2. Age-depth curve of the Byron Bay sediment core. Note samples >26 ka have not been calibrated and hence sedimentation rate for this portion of the core has not been calculated

Sedimentation rates are very low throughout the core. Accumulation rates have not been calculated for the basal estuarine muddy-sand substrates as the dates are not able to be calibrated accurately and hence compared with the calibrated dates of the upper sediments. The upper Sandy Mud layer has a very low average accumulation rate of 0.018 cm/yr (range 0.0013–0.05 cm/yr). The accumulation of the peat layer reduces considerably towards the surface, with a sedimentation rate of 0.094 cm/yr for the lower section of the peat and 0.012 cm/yr for the upper section of peat. The general stratigraphic consistency within the core and the gradual boundaries between sediment layers suggest continuous sediment accumulation with only minor reworking of the sediments between boundaries.

Diatoms

Diatom preservation deteriorated with increasing depth in the core (Figure 3). Diatoms were abundant and well preserved in the surface peat. However, there were no diatoms present in zone 3, in the sand layer, and diatom preservation was very poor in zone 4, with only frustles of the most robust species, *Nitzschia fonticola*, present. Only six diatom species occurred in the sediment core with a relative abundance of >2%, representing a very low diversity. The dominant genera were *Nitzschia*, *Eunotia* and *Pinnularia*. *Nitzschia fonticola* was dominant throughout the core. This species is known to be quite cosmopolitan and in some coastal sites widespread and abundant (Foged 1978; Vyverman et al. 1995). *Nitzschia paleaeformis* was present only in the surface peats, suggesting a change in the depositional environment occurred around 5000 cal. yr BP, marking the commencement of peat formation. *Eunotia soleroii*, *Eunotia flexuosa* and *Pinnularia gibba* were found throughout zone 1 and 2, suggesting a continuously acidic habitat (Sterrenburg et al. 2007). Pyrite, also displayed in Figure 3, was present throughout the core but was detected at very high levels within zone 4, indicating marine conditions were prevalent during deposition of these sediments. The organic content was high throughout the surface peat and in zone 2, negligible in zone 3 and a minor component in zone 4.

Figure 3. Diatom record of the coastal peat sediment core from Byron Bay. Radiocarbon ages >26 ka have not been calibrated

Phytoliths and pollen

The phytolith record (Figure 4) indicates the vegetation surrounding the site has been a grassland fringed with *Melaleuca* forest for the past ~33,500 yr BP. The understorey is dominated by Poaceae, Restionaceae and Cyperaceae species. The tree component was dominated by Myrtaceae *Melaleuca* species type, possibly indicating a single-species tree component of the vegetation community. The tree component is significant in the lower sections of the core until 4581–4959 cal. yr BP, after which it reduces considerably until relatively recently. In the more recent sediments, there are low counts of Myrtaceae phytolith types. The understorey of shrub and grass species dominates the vegetation, forming 80–90% of the vegetation mass throughout the period of peat deposition. Restionaceae and Cyperaceae are peat-forming vegetation types and their abundance increases within the peat litological zones.

The pollen record provides further evidence of a grassland community with fringing *Melaleuca* forests within the catchment area. The tree component is dominated by Myrtaceae *Melaleuca* type and Casuarinaceae. Cyrantheaceae is a dominant understorey shrub, most likely on the margins of the peatland. The pollen data suggest that herbaceous taxa have been the dominant vegetation component of this peat environment for the past ~33,000 yr BP. The upperstorey component is minor but shows distinct fluctuations over time.

Discussion

The coastal peat layer at Byron Bay is 130 cm deep and has accumulated over the past 5000 cal. yr BP, demonstrating a very slow accumulation rate typical of peatlands (Charman 2002). The presence of peat of this age in such close proximity to the ocean indicates that sea levels stabilised in this area approximately 5000 cal. yr BP and the peatland has since been infilling with terrestrially derived sediment. Underlying the peat are sediments of estuarine origin with fine mud particles and very low organic component, indicating higher sea levels in the period preceding 5000 cal. yr BP. The presence of pyrite in these sedimentary layers confirms a strong marine influence on the sediments deposited during this time (Bajpai et al. 2001). This correlates with evidence from Larcombe et al. (1995) and Lewis et al. (2008) on eastern-Australian sea-level fluctuations. The distinct colour change of the estuarine muds at 10,300 cal. yr BP suggests a fluctuation of sea level at this time and a change in sediment origin. Stronger marine influence as indicated by the deposition of sand around 33,000 yr BP indicates a slight increase of sea level or change in coastal geomorphology and hence the proximity of Belongil estuary. However, before this time, up to 42,000 yr BP, the site experienced stable estuarine conditions.

Unfortunately, the diatom record has not contributed significant evidence for the reconstruction of environmental conditions of the coastal plain due to degradation of the silica frustules. Even in the surface peats, only six species were present, indicating very low species diversity. This is typical of peats with their harsh acidic environment (Sterrenburg et al. 2007). However, even six species is a very low diversity for a peatland (Campeau et al. 2000). The species present do indicate acidic freshwater environments (Foged 1978; Vyverman et al. 1995). The introduction of *Nitzschia paleaeformis* when peat accumulation commences is indicative of a change of trophic status that would be expected with the commencement of the accumulation of organic matter.

The diatom record does show a gradual deterioration in the preservation of frustules with increasing depth. This does indicate that diatoms were present at the time of sediment deposition but silica cycling has caused gradual deterioration of frustules present. This is typical of both peat and marine environments. With the two processes occurring at the one location due to both the acid environment of the peat and the saline marine origins, this deterioration

Figure 4. Phytolith and pollen record of the coastal peat sediment core from Byron Bay

is not surprising (Lewin 1960; Bennett et al. 1991). Clearly, more robust species were better preserved and had a higher relative abundance in the sediment core.

In contrast, the phytoliths were well preserved in the peat layer. Phytoliths are very robust silica structures and less prone to deterioration than diatoms (Parr and Sullivan 2005). Comparison of the phytolith and pollen record indicates the strength of using the two indicators together, with the phytolith record indicating the local site vegetation characteristics and the pollen record reflecting vegetation composition changes within the catchment area. Both indicators show varying levels of dominance of the understorey vegetation over the period of peat accumulation. Throughout the past 5000 cal. yr BP, the peatland has been a grassland surrounded by *Melaleuca* forest. The dominant peat-forming vegetation is Restionaceae and Cyperaceae species, which is typical of Australian coastal peatlands (Whinan et al. 2003).

Conclusion

This palaeoecological study found no detectable evidence of sea-level change for the past 5000 cal. yr BP, which indicates that sea levels have possibly been relatively stable on the coastal plain adjacent to Byron Bay during this period, allowing terrestrial processes to dominate and the accumulation of peat to occur. Before this time, the sea level was slightly higher than at present, and the site was shaped by estuarine processes, as evidenced by the constant deposition of estuarine muds. There was a period of very strong marine influence around 33,000 yr BP, which indicates either higher sea levels or a change in the proximity of the Belongil estuary to the core location. This period of estuarine dominance continues until at least 42,000 yr BP.

During the period of peat accumulation, the vegetation was dominated by grassland, with Restionaceae and Cyperaceae being the dominant peat-forming vegetation. The grassland was surrounded by *Melaleuca* forest that contributed significantly to the regional pollen record. Throughout the period of peat deposition, the quality of the interstitial water was freshwater and acidic. These conditions are not conducive to the preservation of diatom frustules and hence the diatom record showed deteriorating preservation throughout the core. This is especially so in the estuarine-influenced section of the core and is typical of marine deposits (Lewin 1960; Dixet et al. 2001).

This study indicated that a multi-proxy methodology in a peatland environment has been able to provide insightful information on the development of a coastal peatland. In combination with an excellent dating record, diatom, phytolith, pollen and lithological changes have contributed to a better understanding of the development of the peatland, and baseline information has been ascertained from which more effective conservation and management decisions can be made.

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