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# Holocene palaeoenvironments and change at Three-Quarter Mile Lake, Silver Plains Station, Cape York Peninsula, Australia

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**Abstract:** Pollen and diatom analyses of organic sediments from Three-Quarter Mile Lake, a perched lake on Cape York Peninsula, north Queensland, indicate that significant changes in vegetation and hydrology occurred during the Holocene. Early Holocene grass-dominated landscapes were replaced in mid-Holocene times by increasingly woody vegetation comprising tropical heathlands, savanna and rainforest. Early-Holocene lake levels fluctuated widely. From mid-Holocene times, lake levels stabilized and water became increasingly acidic as a mature swamp forest developed adjacent to the lake and contributed tannins to the lake water. The timing and character of changes are consistent with those described from the Atherton Tableland in wet tropical Queensland. Holocene dry phases described from the Northern Territory and the western shores of Cape York cannot be identified from Three-Quarter Mile Lake. Rainforest is currently close to its greatest Holocene extent, suggesting that the rainforest-dependent endemic fauna of northern Cape York have been isolated from rainforest blocks to the south throughout the last 10 000 years and, by inference, throughout at least the 120 000 years beyond that.

**Key words:** Holocene palynology, vegetation history, palaeohydrology, fire history, palaeoclimate, Cape York, Australia.

## Introduction

Quaternary palynology in Australia has taken significant strides since the exploratory days of the 1970s; more sites, better interpreted and dated, have made important contributions to understanding the palaeoenvironments of a dry land. That dryness has led to a notable concentration of sites into areas along the well-watered eastern fringe of the continent. Consequently, the palynologically based palaeoenvironmental history for the late Quaternary is largely constructed on key terrestrial sequences from crater deposits in temperate southeastern (Kershaw *et al*., 1991) and tropical northeastern volcanic provinces (Kershaw, 1983, 1994; Turney *et al*., 2001), with augmentation from a few continuous offshore records (Moss and Kershaw, 2000). These records demonstrate late-Pleistocene ecological conditions and climate across eastern Australia dissimilar to present, with generally cooler conditions and pronounced dryness at a broad regional scale leading into and through the last glacial maximum. By comparison, Holocene palaeoenvironments present a picture of relative homogeneity in vegetation and palaeoclimate (Harrison and Dodson, 1993; Hope, 1994; Dodson, 2001), though discernible climatic phases are recognized by some authors. The majority of climatic reconstructions posit the recovery of temperature and rainfall from a nadir at the last glacial to be complete by 10 000 $^{14}$C yr BP. A period of elevated rainfall and temperature characterizes the mid Holocene (about 6000 $^{14}$C yr BP to 4500 $^{14}$C yr BP), followed by an interval of reduced rainfall and temperature between about 4000 $^{14}$C yr BP and 2000 $^{14}$C yr BP and modern conditions since that time. In northern Australia early support for this general pattern was drawn from pollen records of the Atherton Tableland (Kershaw, 1983, 1994), a rainforest stronghold in a region more typically represented by the vast open woodlands and savannahs of the monsoonal wet and dry tropics. A number of lowland Holocene palaeoenvironmental records now exist for the north and northeast of the continent. These include palynological and geomorphological studies, from which a broadly consistent story emerges for Holocene palaeoenvironments across the region. However, it is possible that the spatial clustering of sites towards humid localities masks regional variation in Holocene

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palaeoenvironments. Hints of deviation from the received wisdom, drawn mainly from non-palynological studies, appear in records from areas outside the major foci of palynological activity, although most differences appear to be in the intensity of change rather than direction of change. Geomorphological studies by Lees *et al*. (1990, 1993, 1995), Lees and Clements (1987), Shulmeister and Lees (1995) and Nott *et al*. (1999) point to phases of dryness not documented in pollen records. In particular, Nott *et al*. (1999) argue for a period of early Holocene aridity from around 8000 $^{14}$C yr BP to 6000 $^{14}$C yr BP, based on emplacement of longitudinal dunes at the Rosie Creek dunefield near the western shores of the Gulf of Carpentaria. This view is at odds with regional pollen evidence for steadily increasing effective precipitation for the period, although Longmore (1998) also argues for a dry mid Holocene based on pollen and lake level records from Fraser Island on the central Queensland coast. The need for detailed Holocene (and longer) pollen records for the northern region, independent of the Atherton Tableland, has long been recognized and this paper presents the results of pollen, charcoal and diatom analyses from Three-Quarter Mile Lake, a perched dune lake on the coastal plain 38 km northeast of Coen, Cape York Peninsula (Figure 1). The lake is well placed to examine Holocene climatic and environmental change in northern Australia, being remote from the physiographic influence of the Tablelands, and close to the major biogeographic divide between northern Cape York rainforests, which have strong botanical and faunal links with New Guinea (Abrahams *et al*., 1995, Crisp *et al*., 2001), and more 'Australian' rainforests of the coastal ranges and tablelands to the south.

## The regional setting

Cape York Peninsula is a large area of relatively undisturbed tropical landscape in far northeastern Australia. The western and central Cape is dominated by Cainozoic duricrusts and sand plains carrying sclerophyllous open forests whilst in the east, granite and metamorphic mountains add topographic, climatic and biological diversity to the region. Large areas of the eastern uplands, particularly in the McIlwraith and Iron Range areas, support tropical rainforest/swamp forest/open forest mosaics modulated by soil, topography and microclimate (Lavarack and Godwin, 1987). Palynologically distinctive elements of the upland rainforests include *Podocarpus neriifolius* and *Callitris macleayana* (P.S. Valentine, personal communication, 2002). The ranges are separated from the Coral Sea coast by a narrow alluvial and colluvial plain supporting *Melaleuca* and *Eucalyptus* woodlands and littoral vine thickets (Lavarack and Godwin, 1987). Coastal landscapes feature siliceous coastal dunes, oligotrophic swamps, salt flats and mangroves with tropical heath, swamp, saltmarsh and mangrove communities, respectively. Major streams, such as the Rocky River, Massey Creek, Chester River and Nesbitt River, originate in the McIlwraith Range and cross the coastal plain, where well-developed gallery rainforests contribute to the complex patterns of vegetation at local and regional scales.

Regional climates are strongly influenced by the Australian monsoon. Rainfall is markedly seasonal, with maxima in summer months between December and March. The intensity of winter seasonal drought is modified by orographic rain triggered by interaction between southeasterly trade winds and mountains along the eastern coast of the Cape. These areas receive a significant boost to dry season rainfall and support numerous perennial streams as a result. Mean rainfall totals are not as high as on the wet tropical Atherton Tablelands, though climatic data are drawn from a sparse network of recording stations and may significantly underestimate rainfall in the McIlwraith and Iron Ranges. Nonetheless, the eastern slopes and uplands of Cape York are wet tropical whilst climates at lower elevations are more strongly seasonal. Temperatures are high all year. Wet-season mean maxima at Lockhart River, just north of the study area, hover between 30°C and 32°C whilst dry season maxima average 27°C. Mean

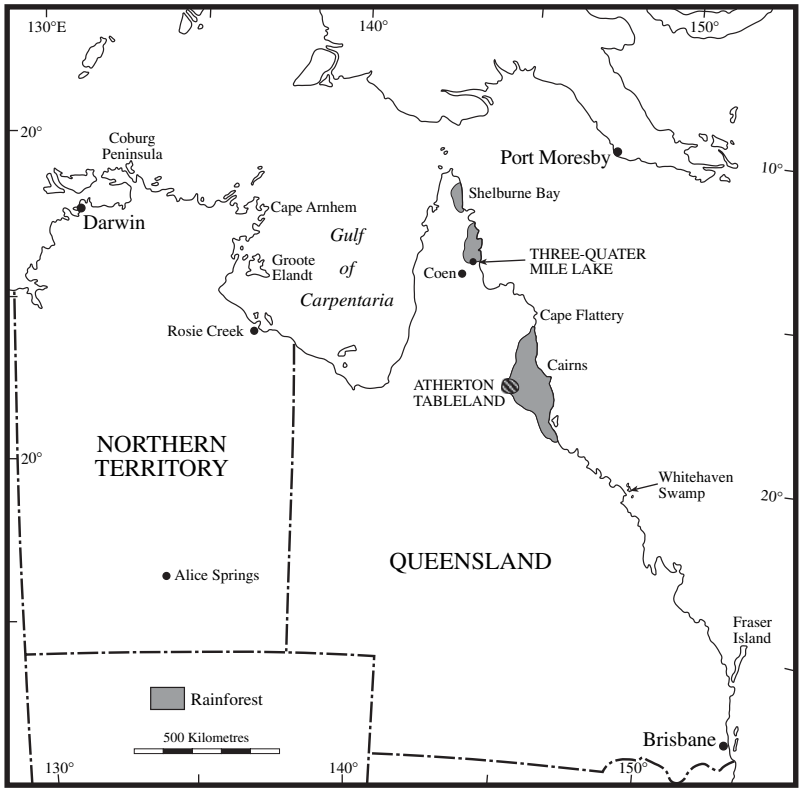


**Figure 1** Location of study site and places mentioned in the text

temperature minima in wet and dry seasons are approximately 23°C and 19°C, respectively. Humidity is high all year, particularly along the eastern coast. Tropical cyclones regularly affect Cape York, bringing extreme rainfall and destructive winds to exposed slopes and coasts.

## The lake and surrounds

Three-Quarter Mile Lake is a perched lake resting on a siliceous coastal dune of probable Pleistocene age (Figure 2). The lake is circular, with a diameter of 750 m. There is no inlet but water drains westerly from the lake along a shallow outlet towards Scrubby Creek, which lies about 500 m from the western edge of the dune. The outlet channel is lushly vegetated with swamp forest and gallery rainforest. The lake is fringed with a swamp forest comprising stately *Melaleuca leucadendra* trees, variously festooned with ferns, especially *Stenochlaena palustris*, and the leguminous climber *Vandasina retusa*. A discontinuous fringe of water lilies (*Nymphaea violacea* and *Nymphoides* cf. *crenata*) occurs around the lake circumference to a maximum water depth of approximately 1.5 m. The maximum lake depth measured in June 1997 was 3.8 m. The water is strongly coloured (Secchi depth less than 50 cm) by tannins.

Organic lake sediments overlie gleyed medium sandy clay similar in composition and texture to sediments of an alluvial fan exposed on the right bank of the Rocky River. The fan is clearly visible on aerial photographs and has been truncated by a shoreline that also trims the eastern edge of the adjoining dune. The trim line can be traced northwards from the Rocky River. Along this reach it truncates the seaward edge of the Pleistocene dune, drains several former dune lakes adjacent to Three-Quarter Mile Lake and cuts additional fans associated with earlier incarnations of Scrubby Creek and the Chester River. The Pleistocene dune has been scalloped along its western margin by migration of Scrubby Creek, though that creek is now located well to the west of the inland edge of the dune.

A complex mosaic of vegetation types occurs near Three-Quarter Mile Lake. Land surfaces associated with Scrubby Creek and nearby drainages are dominated by consolidated sandy clays with occasional surficial sand bodies. They support open savanna vegetation with abundant grass and medium trees, particularly *Eucalyptus tetrodonta*, *Corymbia tessellaris* and *Lophostemon suaveolens* (Lavarack and Godwin, 1987). Swamps are dominated by *Melaleuca* woodlands (*M. viridiflora* and *M. nervosa*) and sedgelands, while stands of *Grevillea pteridiifolia* are distinctive features of better-drained sites.

The Pleistocene dune is densely clothed with a closed canopy tropical heath dominated by *Neofabricia myrtilifolia, Asteromyrtus brassii* and other myrtaceous shrubs (Lavarack and Godwin, 1987). Gaps in the canopy give succour to seedlings of rainforest plants such as *Rapanea* sp., *Syzygium forte* and *Diospyros* sp. Vegetation on the Pleistocene dune has been mapped by Lavarack and Godwin (1987) as 'coastal vine complex' in recognition of the rainforest floristic elements

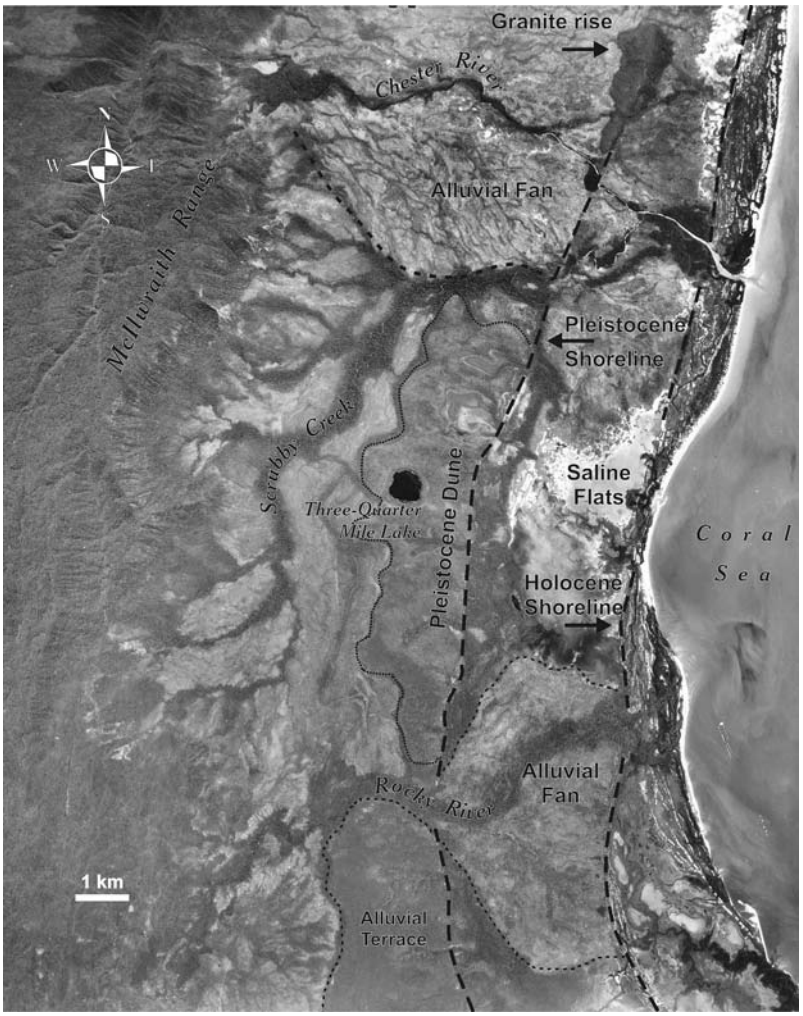


**Figure 2** Aerial photograph interpretation of the Three-Quarter Mile Lake study site and surrounding landscape features

present. It is probable that long-term persistence of the heathland community depends on recurrent fire to suppress rainforest expansion from creek lines and onto the dune.

Swamp forest in the creek draining Three-Quarter Mile Lake contains *Pandanus* sp., *Deplanchea tetraphylla*, *Chionanthus* sp., *Livistona* sp., and *Melicope elleryana*, among numerous others. Mangroves, dominated by Rhizophoraceae, form a fringe in the estuarine reaches of drainages such as the Rocky River and Chester River, and occur as a narrow fringe on sheltered stretches of the coast, which at present lies some 5.5 km east of the lake.

## Methods

Two cores were collected from Three-Quarter Mile Lake. The main core site is at the approximate centre of the lake whilst the second is approximately 100 m from the western shore. Cores were collected by driving a length of 50 mm diameter PVC tubing into the lake floor. On recovery, cores were sealed and returned to the laboratory for description and sampling. Pollen counting and identifications were carried out at the Centre for Palaeoecology and Palynology, Monash University, Melbourne. Cores were described according to sediment type and organic content. Sediment samples for pollen analysis were taken at 5 cm intervals down the core. A measured volume of each untreated sediment sample was mixed with a known quantity of exotic *Lycopodium* spores to aid pollen and charcoal concentration determinations. Pollen extraction followed standard techniques including disaggregation in 10% tetrasodium pyrophosphate ($Na_4P_2O_7$), digestion of silicates in hydrofluoric acid (HF) and removal of extraneous organic material using acetolysis and cold Schultz treatments (Faegri and Iverson, 1966; Erdtman, 1969). Residues were suspended in liquid glycerol for permanent mounting on microscope slides.

Pollen identifications and counting were carried out on an Olympus light microscope. Pollen counts proceeded until at least 100 pollen and fern spores were identified. The results are presented in a pollen diagram created using the spreadsheet program TILIA and its counterpart TILIAGRAPH (Grimm, 1988). Values in pollen diagrams are percentages of the pollen sum, which includes all dryland pollen types. The relative abundance of microscopic charcoal was estimated by corresponding counts of charcoal particles and *Lycopodium* spores, in each pollen sample. Charcoal was defined as any opaque, black object in the field of view. While this method allows the determination of particle abundance per unit volume of raw sediment, it does not provide an estimate of charcoal volume, and is intended for comparison only between samples within the Three-Quarter Mile Lake core.

Samples for diatom analysis were taken at 10 cm intervals, and prepared following standard protocols (Battarbee, 1986; Krammer and Lange-Bertalot, 2000b). Diatoms were fixed in Naphrax and counted at 1000 × magnification under transmitted light microscopy. Taxonomy follows Krammer and Lange-Bertalot (1991, 1999a,b, 2000a,b). Partial valves were counted, in the case of biraphid species, only where proximal fissures of both raphes could be identified or, in the case of araphid or centric species, where more than half the entire valve was present. Diatom taxa are expressed as a percentage of the entire assemblage.

Four AMS radiocarbon analyses were performed on pollen from 18 cm, 49 cm, 103 cm and 145 cm depth in core. AMS determinations were carried out by the University of Waikato Radiocarbon Dating Laboratory, Hamilton, New Zealand. Pollen used for dating were extracted from sediment by the cold Schultz method. Acetolysis was avoided to remove the possibility of contamination by old carbon contained in acetic annhydride. Calibrated ages were determined with CALIB (version 5.0) (Stuiver and Reimer, 1993) using the Southern Hemisphere standard shcal104.14c (McCormac *et al*., 2004).

## Results

### Stratigraphy and chronology

Cores from Three-Quarter Mile Lake comprise 150 cm of amorphous organic mud overlying stiff, blueish-grey sandy clay. The organic sediments are water-saturated and have so little coherence that the upper parts of the core remain fluid and are difficult to sample precisely. There is no discernable stratification. The basal sandy clays contain coarse, poorly sorted, angular quartz and feldspar granules and closely resemble the alluvial fan deposits exposed in the banks of the Rocky River, where fan sediments are overlain by aeolian sands of the dune on which Three-Quarter Mile Lake is situated. It is probable that the sandy clay unit at the bottom of Three-Quarter Mile Lake is also fan material. AMS radiocarbon dates suggest deposition of organic sediments began at approximately 10 000 $^{14}$C yr BP (cal. 9913–10 338 BP), though the dune upon which the lake sits, and the lake basin itself, are significantly older. The upper two dates are reversed (Table 1) and in the absence of an exotic pollen horizon marking the European era from the early nineteenth century it is not possible to provide a chronology robust enough to support calculation of pollen or diatom fluxes.

### Diatoms

Fifty-one species of diatom, representing 26 genera and eight families, were identified. Preservation of diatoms is poor in all samples, but particularly so at and below 90 cm depth. Whole valves, particularly from larger species, are rare. Damage to frustules appears to be largely mechanical, with little evidence of chemical degradation. Counts are low as a result of this poor preservation, ranging between 99 and 181 individuals, with a mean count of 128 individuals. Samples at 140, 130, 100 and 90 cm depth are so poorly preserved that no counting was attempted. Three diatom zones are identified (Figure 3). In the following description, the abbreviation 'aff.' refers to fossil taxa which have a morphological affinity to types described in the literature but whose identification remains uncertain. The abbreviation 'var.' refers to known morphological variants of described species.

**Table 1** AMS $^{14}$C results

| Depth | Lab. no. | $^{14}$C age | Calibrated age (1σ) | Calibrated age (2σ) | Standard |
|---|---|---|---|---|---|
| 18 | WK 17112 | 1780 ± 37 | 1569–1694 BP | 1535–1720 BP | shcal104.14c |
| 49 | WK 17113 | 1501 ± 33 | 1304–1358 BP | 1295–1395 BP | shcal104.14c |
| 103 | WK 7891 | 8330 ± 70 | 9134–9402 BP | 9302–9445 BP | shcal104.14c |
| 145 | WK 7892 | 9090 ± 70 | 9955–10 269 BP | 9913–10 388 BP | shcal104.14c |

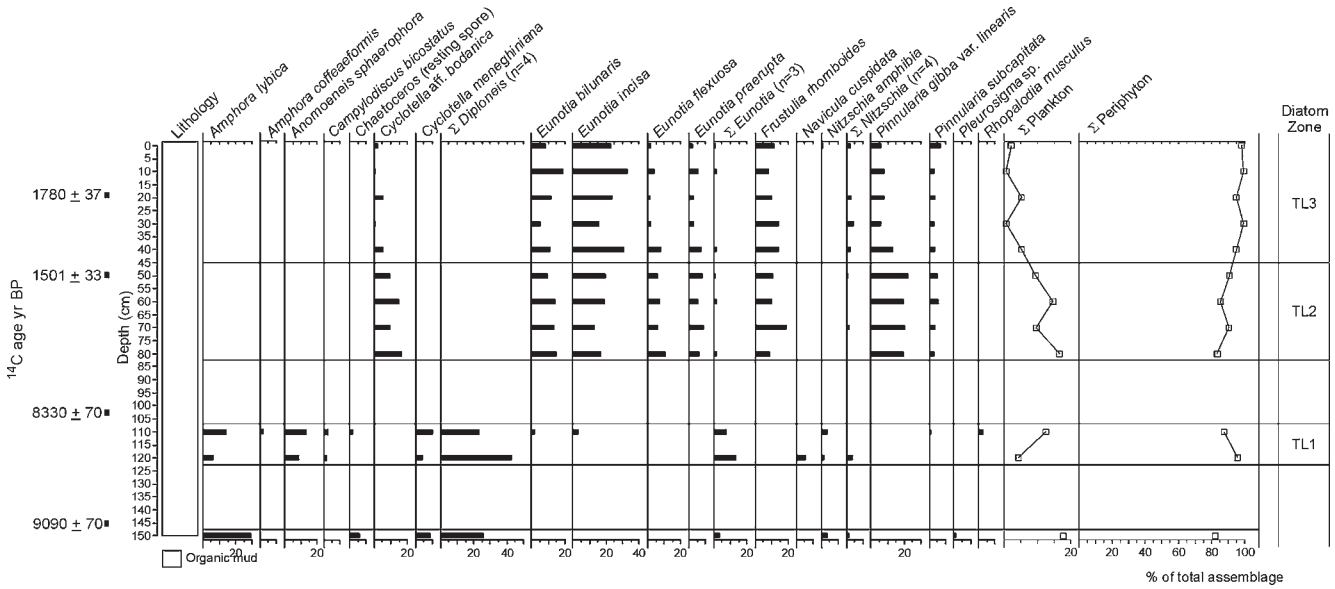


**Figure 3** Fossil diatom diagram for the Three-Quarter Mile Lake core. Values are percentages of total identified diatom assemblages

*Diatom Zone TL1 (120–110 cm ~ 8200–9000 $^{14}$C BP)*
Samples in this zone are dominated by *Diploneis* spp. These were commonly the central area and or partial valves which are diagnostic of the genus but too poorly preserved to be assigned a species identifier. Other common taxa were *Amphora lybica*, *Anomoeneis sphaerophora*, with *Cyclotella meneghiniana* and species of *Eunotia* also frequently recorded.

*Diatom Zone TL2 (80–50 cm ~ 6500–4300 $^{14}$C BP)*
Common taxa in this zone are *Cyclotella* aff. *bodanica, Eunotia* species (particularly *E. bilunaris* and *E. incisa*), *Frustulia rhomboides* and *Pinnularia gibba* var. *linearis*. All taxa fluctuate subtly through the zone, but no trends are apparent.

*Diatom Zone TL3 (40–0 cm ~ 3500–0 $^{14}$C BP)*
*Eunotia incisa* is the dominant species in this zone, with an average representation of 25% of the total assemblage. *E. bilunaris* is subdominant, reaching a maximum representation at 10 cm depth. *Frustulia rhomboides* is consistently represented while *Cyclotella bodanica* and *Pinnularia gibba* var *linearis* are more poorly represented that in the previous zone and become less common as depth decreases.

## Pollen

The Three-Quarter Mile Lake pollen diagram (Figure 4) shows the percentage occurrence of 61 pollen and spore taxa. All can be assigned to parent taxa still found in the modern regional vegetation. The diagram is divided into three pollen zones for ease of description. The zones are defined with reference to the pollen of Three-Quarter Mile Lake and have no regional correlational significance.

*Zone TL1 (150–90 cm ~ 9500–7500 $^{14}$C BP)*
Dryland pollen spectra are dominated by pollen of Casuarinaceae, *Eucalyptus* type, Poaceae and, to a lesser extent, *Melaleuca* type. Other dryland taxa with minor and, often sporadic, representation include *Callitris*, Chenopodiaceae, *Dodonaea*, *Corymbia polycarpa* type, *Gonocarpus*, *Neofabricia* type and *Pandanus*. Rainforest taxa are very poorly represented, but include minor and sporadic occurrences of *Podocarpus*, *Petalostigma*, Rubiaceae and Urticaceae. Aquatic pollen types are also poorly represented, with the exception of *Typha*, which is abundant through much of the zone. Cyperaceae, *Macharina* type and the aquatics *Myriophyllum*, *Nymphaea* and *Nymphoides* are present but are never abundant. Pteridophyte spores are poorly represented, while mangrove pollen are not recorded in this zone. There is virtually no charcoal in zone TL1 below a depth of approximately 95 cm, at which level a short-lived peak in charcoal concentration occurs toward the upper boundary of the pollen zone.

*Zone TL2 (85–60 cm 7500–5000 $^{14}$C BP)*
Percentages for Poaceae, though consistently strong, are noticeably lower than in the previous zone. Casuarinaceae and *Melaleuca* type pollen remain well represented. *Callitris* attains its strongest values for the record, while other dryland taxa with more modest representation include *Acacia*, Asteraceae, *Celtis*, Chenopodiaceae, *Dodonaea*, *Eucalyptus* type, *Corymbia polycarpa* type, *E. tetrodonta* type, *Lonchocarpus* type, *Neofabricia* type and *Pandanus*. Rainforest pollen types are best represented by *Podocarpus*, *Trema*, *Ilex*, *Macarangal Mallotus*, *Olea*, *Petalostigma* and *Terminalia*, albeit at low frequencies. The most abundant aquatic elements are Cyperaceae (*Macharina* type and *Leptocarpus* type), while *Typha* is very poorly represented compared with the previous zone. Pteridophyte spores occur more frequently than in the previous zone, and include unidentified monolete spores, *Stenochlaena* and *Selaginella*. Mangrove pollen types include strong values for *Rhizophora stylosa* type, and minor occurrences of *R. apiculata* type, *Avicennia* and *Bruguiera* type.

Charcoal concentrations rise gradually at the base of the zone before rising abruptly at a depth of 72 cm. Above 72 cm, charcoal is consistently present though values vary episodically.

*Zone TL3 (55–0 cm ~ 5000–0 $^{14}$C BP)*
In this zone the most strongly represented dryland taxa are Poaceae, Casuarinaceae, *Eucalyptus* type and *Melaleuca* type. Other taxa with consistent representation are *Acacia*, *Callitris*, *Dodonaea*, *Corymbia polycarpa* type, *Eucalyptus tetrodonta* type, *Neofabricia* type and *Pandanus*. Taxa present at lower frequencies include *Banksia*, *Celtis*, Chenopodiaceae, Leguminosae undet. and *Lonchocarpus* type. Values for rainforest taxa appear stronger than in previous zones, major elements being *Podocarpus*, *Trema*, *Mallotus*, *Olea* and *Petalostigma*. The aquatics are dominated by *Leptocarpus* type and *Cyperaceae*,

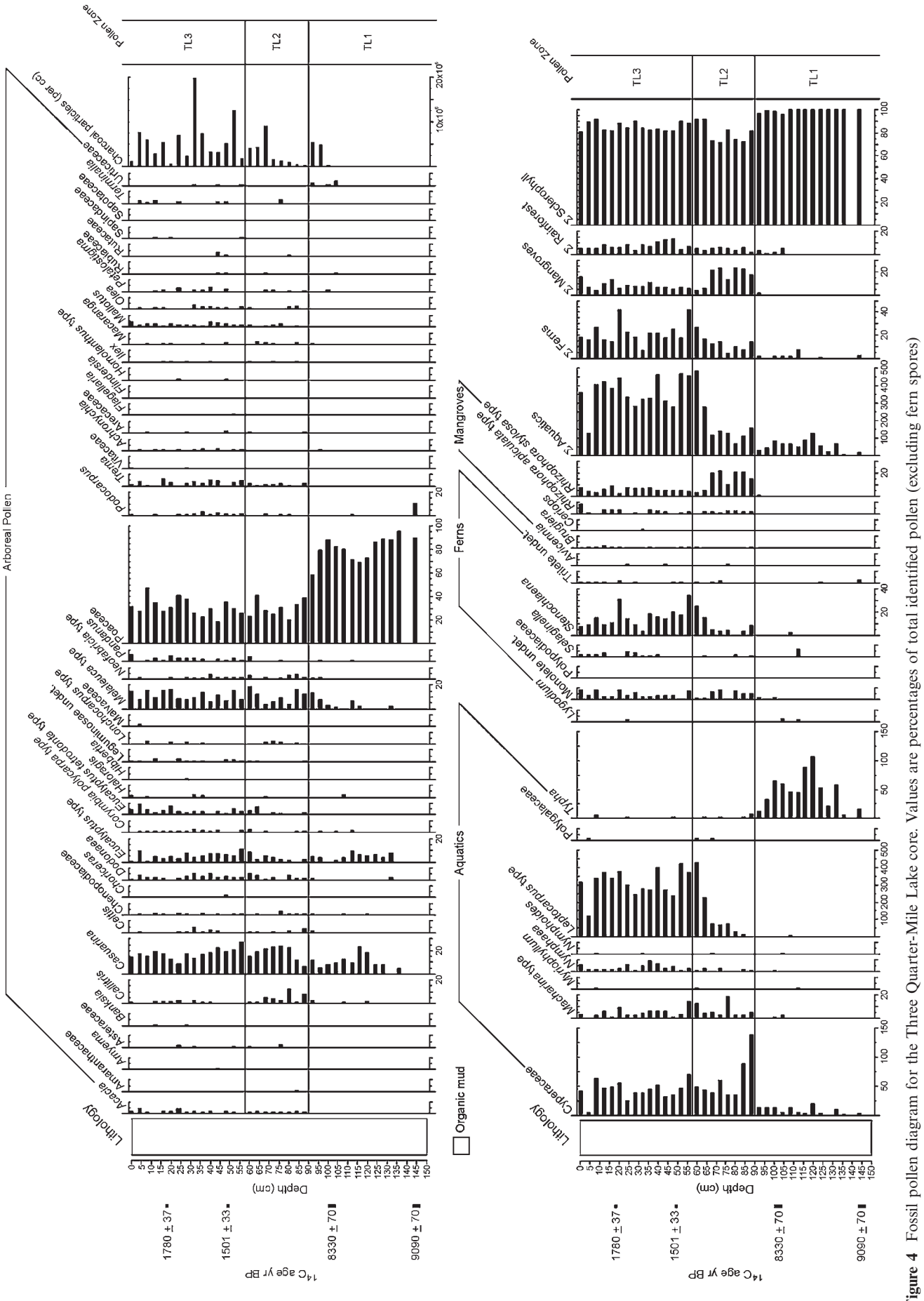


**Figure 4** Fossil pollen diagram for the Three Quarter-Mile Lake core. Values are percentages of total identified pollen (excluding fern spores)

with *Macharina* type and *Nymphaea* consistently recorded at lower frequencies. Pteridophyte spores again are dominated by monolete undet., *Stenochlaena* and *Selaginella*. The mangrove elements *Rhizophora stylosa* and *R. apiculata* occur consistently at low frequencies. Charcoal concentrations in this zone fluctuate widely. A major peak occurs at ~32 cm. The charcoal concentration in the uppermost sample is relatively low though clear evidence of recent fire, including scorching of tree trunks and presence of macroscopic charcoal on the soil surface, can be found in the heath community surrounding the lake.

## Interpretation and discussion

Pollen and diatoms of Three-Quarter Mile Lake record a series of environmental changes in the period since sedimentation began in the lake at about 10 000 $^{14}$C yr BP. Diatom assemblages at 150, 120 and 110 cm depth imply oligo- to mesosaline waters (*C. menehiniana, Nitzschia amphibia*, *Chaetoceros* sp.), or eusaline to hypersaline waters (*Amphora coffeaeformis, Campylodisus clypeus, Rhopalodia musculus*) (Gasse *et al*., 1995; Gell, 1997; Gasse, 2002). The halophytic species *Navicula cuspidata* (Leung *et al*., 2003: 21) was recorded in small numbers at 120 cm depth and, in all instances, their tests exhibited craticula–reportedly a response to elevated osmotic pressure (Krammer and Lange-Bertalot, 2000b: 36). The formation of these rigid rib-like processes (costae) within the frustule is evidence of osmoregulation, presumably to protect the cell from rupture resulting from increased osmotic flow as a result of intracellular solute concentrations being higher than those of the lake water. This suggests salinities in the lake were at the lower end of the tolerance spectrum for this species. Heavily ornamented *Chaetoceros* resting spores were also apparent in this sample, indicating unfavourable conditions. *Typha,* the dominant aquatic vascular plant in the pollen record below 95 cm depth, is known to be moderately salt tolerant, but cannot grow in moderately meso- to polysaline waters (Glenn *et al*., 1995; Lombardi *et al.*, 1997). We interpret this as evidence of variable salt concentrations during the early lake phase associated with variable or ephemeral water levels.

Dryland vegetation in the vicinity of the lake was open and grassy. The occurrence of rainforest associated pollen, such as *Podocarpus* indicates the presence of rainforest within the pollen catchment of the lake. Modern rainforests occur as gallery forests along river courses and as montane forests in the MacIlwraith Ranges west of the lake. *Podocarpus* is a genus associated with the montane rainforests at present and it is likely that early Holocene rainforests contributing pollen to the lake were also growing in the mountains. Non-rainforest woody vegetation was dominated by Casuarinaceae, as are the modern surfaces of inactive alluvial fans in the vicinity of the study site today. Rainforest-related taxa adapted to dry environments, such as *Petalostigma*, are frequently found in such settings in the modern flora and were very likely so in the early Holocene too. There is little indication of swamp forest around the lake, or of closed *Neofabricia* heath on the dune at this time. Despite the predominance of open, grassy vegetation, fire seems to have been of little importance in the early Holocene landscape.

Significant changes in lake and dryland environments begin at a depth of about 80 cm in the core, corresponding to an inferred radiocarbon age of approximately 5000 $^{14}$C yr BP. Diatom floras indicate a change in lake character from a fluctuating 'brackish' water body to one of permanent fresh water, subject to increasing influence on water quality exerted by tannins generated in the surrounding vegetation. The *Typha*-dominated marginal lake vegetation was replaced by the modern complement of Cyperaceae, water lilies and ferns. The change in hydrological regime reflects increasingly effective rainfall and is accompanied in the dryland vegetation by encroachment of the open grassy landscapes by woody trees.

The strongest values for *Callitris* pollen in zone TL2 are consistent with a mid-Holocene expansion of woody vegetation, as the likeliest contributing species (*C. macleayana*) has a marked preference for growing at the margins of rainforest. It is excluded from mature closed forests by being overtopped and shaded out by canopy-forming trees and cannot persist in heath communities, which depend upon an active fire regime to prevent successional replacement by rainforest. Expansion of woody vegetation was accompanied by a more active fire regime, which may reflect heavier and more continuous fuel loads on the dune surface around the lake.

The occurrence of mangrove pollen from middle Holocene times reflects movement of the coastline closer to the pollen site during the final stages of marine transgression. Air photo analysis places the mid-Holocene shoreline within 2.5 km of Three-Quarter Mile Lake, approximately 3 km closer than present. The peak in mangroves, especially *Rhizophora*, corresponds to the so-called 'big swamp' phase recognized in northern Queensland and the Northern Territory from 7000 to 5000 $^{14}$C yr BP (Woodroffe *et al*., 1985; Crowley *et al*., 1990; Grindrod, 1995), when development of expansive mangrove communities coincided with adjustments to coastal sedimentation as relative sea level stabilized. Subsequent declines in mangrove percentages at Three-Quarter Mile Lake likely reflect both a narrowing of the intertidal zone and the increasing distance between the lake and the prograding coastline.

In the uppermost parts of the Three-Quarter Mile Lake record, the trend to replacement of open vegetation by trees continues. Eucalypts (particularly *E. tetrodonta*) and *Melaleuca* formed major components of sclerophyll and swamp forests, respectively, and an increased occurrence of wet rainforest-associated taxa, such as *Terminalia*, *Celtis*, *Macaranga* and *Mallotus* suggests consolidation of rainforest in the uplands and in gallery forests along the channels of the Rocky River and Scrubby Creek.

The charcoal record from Three-Quarter Mile Lake is notable for the negligible values below, and generally high values above, 100 cm depth in the core. Much is written about the relative ecological significance of natural and anthropogenic fire in late-Pleistocene and Holocene Australia (Clark, 1983; Singh and Geissler, 1985; Head, 1989; Kershaw *et al*., 1997, 2002), and modern indigenous landscape management through the deliberate application of fire is well documented (Kimber, 1983, Braithwaite, 1991, Bowman *et al*., 2004). The apparently strong and sustained increase in fire in the Three-Quarter Mile Lake catchment beginning around 8000 $^{14}$C yr BP coincides with the general Holocene trend towards more heavily wooded vegetation from the open, grassy environments of the late Pleistocene. Consequently the record may simply reflect the change to a vegetation type that is more capable of carrying a fire, or at least of contributing a substantive charcoal signature to the lake sediments. Alternatively, the change may herald fire management strategies by people intent on maintaining a relatively open landscape against the prospect of forest or woodland encroachment on a regional scale (Luly, 2001a,b). The latter circumstance seems plausible given that modern fire management by indigenous people is commonly justified in terms of maintaining open vegetation for the

benefits of access, useful plant and animal management, and pest control (Bowman and Panton, 1993; Bowman, 1998). On the basis of evidence available we cannot discriminate between natural and anthropogenic factors underlying the more active fire regime.

## Regional implications

Climatic and vegetational events reconstructed from Three-Quarter Mile Lake are consistent with general patterns exhibited on the Atherton Tableland and elsewhere in northern Australia. Pleistocene climates close to the LGM on Cape York were apparently dry enough to have completely removed any pre-Holocene organic fill in the lake basin by erosion, oxidation or burning. Increasingly effective precipitation is evident from around 9000 $^{14}$C yr BP, in good agreement with records from the Atherton Tableland, where renewed swamp sedimentation is dated to around 9500 $^{14}$C yr BP at Bromfield Swamp, 9200 $^{14}$C yr BP at Lynch's Crater, 8000 $^{14}$C yr BP at Lake Euramoo and 7200 $^{14}$C yr BP at Quincan Crater (Hiscock and Kershaw, 1992). Lowland coastal swamp sedimentation begins around 9000 $^{14}$C yr BP in the western Gulf of Carpentaria on Groote Eylandt (Shulmeister and Lees, 1995), and at 7000 $^{14}$C yr BP on Queensland's central east coast at Whitehaven Swamp (Genever *et al*., 2003). As is the case at Three-Quarter Mile Lake, each of these sites appears to maintain continuous lake and/or swamp sedimentation from the early Holocene until the present. An important feature of the records is the tentative beginnings to swamp establishment. This is particularly true at Groote Eylandt, Three-Quarter Mile Lake and Whitehaven Swamp where, in contrast to the long late-Quaternary sequences of the Atherton Tableland, organic sedimentation begins in sandy basins excavated or laid bare on aeolian landscapes during late-Pleistocene aridity. The records consistently indicate shallow and variable lake levels early in the Holocene history of these lowland sites.

The significance of aeolian processes in the Holocene history of coastal northern Australia has been emphsized by a number of authors, especially those working on western Cape York and in the Northern Territory. Lees (1992) and Lees *et al*. (1990, 1995) interpret widespread dune mobility on the eastern shores of the gulf of Carpentaria (beginning as early as 9500 $^{14}$C yr BP and continuing until 6500 $^{14}$C yr BP) as a reflection of an enhanced sediment supply to the coast consequent upon sea-level rise (see also Lees and Clements, 1987, Nott *et al*., 1999). Ascribing sand mobility to coastal processes in the early part of this period seems problematic given that sea level was at about $-20$ m AHD at 9000 $^{14}$C yr BP and the former coastline was, therefore, many kilometres from its present position on the low-gradient continental shelf of northern Australia. No indication of comparable dune instability is recorded at either Three-Quarter Mile Lake or Whitehaven Swamp. Likewise, claims for pronounced aridity between 8000 and 6000 $^{14}$C yr BP (Nott *et al*., 1999) based on activity of linear dunes in the Rosie Creek dunefield, seem at odds with east coast pollen sequences, which indicate steadily increasing effective precipitation. The Rosie Creek findings are, however, consistent with the occurrence of sand lenses in the Groote Eylandt pollen core at intervals between 9000 and 7500 $^{14}$C yr BP, which are explained by Shulmeister (1992) as indications of dune slip-face gravity flows and are considered to be evidence of sparser vegetation than that which effectively binds dune sand today. The number of western Gulf and Cape York sites with evidence for early Holocene aridity based on sand movement is not easily dismissed, especially as explanations for dune activity for the period due to marine transgression are difficult to sustain. The relatively early and persistent recovery of effective rainfall in eastern Cape York and on the Atherton Tableland probably owes its origin to orographic rain brought to eastern slopes by the southeasterly trades during the winter dry season. The relative dryness suggested for early-Holocene continental shelf localities in northeast Queensland, where coastal environments were dominated by saltmarsh (Grindrod *et al*., 1999, 2002), is consistent with this hypothesis as the continental shelf sites, and hence the contemporaneous coastline, are remote from strong topographic influences.

There is general agreement in pollen records across the region that the mid Holocene was wetter than present. In the best-dated sequences from the Atherton Tableland the wettest times were between 7000 and 4500 $^{14}$C yr BP. A moister mid Holocene is also apparent at Whitehaven Swamp (Genever *et al*., 2003) and from Groote Eylandt (Shulmeister, 1992, Shulmeister and Lees, 1995). At Three-Quarter Mile Lake, rainforest expansion is preceded by markedly increased representation of the rainforest-associated taxon *Callitris* after 8000 $^{14}$C yr BP. This is followed by increases in *Podocarpus*, *Acronychia*, *Olea*, *Petalostigma*, *Trema* and *Mallotus*, indicating a more significant presence of rainforest near the lake relative to early Holocene times. The increased representation of the latter two taxa, which are successional or edge-dwelling taxa, is sustained to the present and suggests that the modern rainforest remains in a robust, expansionary phase.

The pattern of wetter mid-Holocene climates extends beyond eastern Australia into the arid core of the continent (Luly, 1993, 2001a; Cupper, e*t al*., 2000) suggesting that the phenomenon is widespread and the case for a dry mid Holocene advanced from Fraser Island (Longmore, 1997, 1998; Longmore and Heijnis, 1999) stands as a stark anomaly in need of resolution.

Although mid-Holocene climates appear to have favoured expansion of rainforest, there is little indication that the boundaries of major rainforest blocks experienced significant expansion relative to today. Three-Quarter Mile Lake lies adjacent to a major biogeographical boundary between rainforests of northern Cape York and those of the rest of Queensland. Forests of the McIlwraith Range and Rocky River give way to an expanse of grasslands, woodlands and savanna that impedes movement of rainforest-dependent organisms between northern and southern rainforest blocks. The boundary is especially important for rainforest-dependent birds, mammals and butterflies, many of which to the north have stronger affinities with the biota of New Guinea than they do with the more 'Australian' rainforests to the south (Barlow, 1994; Abrahams *et al*., 1995; Crisp *et al*., 2001). Pollen analyses from Three-Quarter Mile Lake indicate that the Cape York rainforest is currently close to its maximum extent for the last 10 000 years and that the boundary between rainforest blocks is at least that old. Given the similarity in rainforest histories at Three-Quarter Mile Lake and on the Atherton Tableland it is not unreasonable to conclude from the longer Atherton pollen records, and from the long pollen records from ancient Lake Carpentaria (Torgersen *et al*., 1988; Chivas *et al*., 2001) that the northern and southern rainforest blocks have remained functionally separate for 120 000 years or more.

The Three-Quarter Mile Lake pollen and diatom record indicates relative stability in the lake system and its catchment since mid Holocene times. A modest attenuation of rainforest representation since mid Holocene times is consistent with Atherton Tableland and Whitehaven Swamp records, though the trend towards drier conditions is much more modest than is suggested by dune activity on the Coburg Peninsula, Shelburne

Bay and Cape Flattery (Lees *et al.*, 1990), Groote Eylandt (Shulmeister and Lees, 1995), Cape Arnhem (Lees *et al.*, 1995) and as far afield as the east Kimberley region of northwestern Australia (Lees, 1992) and the Australian desert (Luly and Jacobsen, 2000). The location of Three-Quarter Mile Lake on the flanks of the McIlwraith Range may render the site insensitive to minor changes in effective rainfall that, while potentially widespread, are insufficient to produce a detectable response in local vegetation or landscape.

## Conclusions

Pollen and diatom floras preserved in Three-Quarter Mile Lake record a pattern of Holocene lake and vegetation change broadly consistent with those described elsewhere in north-eastern Australia. Early Holocene grasslands were progressively replaced by tropical heath, woodland and gallery rainforest as lake levels rose and stabilized in the mid Holocene. Differences between the Three-Quarter Mile Lake record and those of sites on western Cape York and western Gulf of Carpentaria partly reflect differences in sensitivity between the sites, however, there may also be real differences in rainfall patterns induced by the geometry of continental shelf and coastal ranges and their effects on the major rain-bearing systems. There is a need for reconstructions of vegetation histories from these areas to better discriminate between potential causes of sand instability on the western coast of Cape York and in the western Gulf of Carpentaria. The phenomenon of mid-Holocene aridity on Fraser Island remains an enigma.

The minimal representation of rainforest pollen in the early Holocene record from Three-Quarter Mile Lake suggests that, as on the Atherton Tableland, glacial maximum age climates forced the rainforests of the McIlwraith Range into retreat and, by inference, the separation of Cape York rainforests from those to the south has been in place for a substantial time–at least 120 000 years, coincident with the last major expansion of Australia's wet tropical forests and before the enhanced influence of fire that accompanied human settlement of the region.

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