APPENDIX 2

PALAEOENVIRONMENT: NORTH-WEST AUSTRALIA

The following discussion presents a broad-brush account of north-west Australia's palaeoenvironments from about 100,000 years ago, by which time the last glacial period was well underway. This area by and large encompasses the Great Sandy Desert, the Kimberley, the inland Pilbara, and the Pilbara coast and plains to Shark Bay (Figure A2.1). This background analysis is intended to set the scene for the modelled Late Pleistocene and Holocene environments developed for the Fortescue Marsh area, which appears in Chapter 3.

Environmental reconstructions pertaining to the earliest times rely solely on one source: a pollen core (GC17) taken from the Pilbara continental shelf about 60 km west of Cape Range Peninsula (van der Kaars and De Deckker 2002; van der Kaars, De Deckker and Gingele 2006). These data mostly pertain to the area around the north-west Pilbara coast. Van der Kaars (1991) is important as a comprehensive coverage of the vegetation likely to have been present across the continental shelf during the period of low sea levels.

A brief, general comment about the Pilbara as a biogeographic refugium is warranted at this juncture. This region is generally recognised as a globally significant area of high, long-term species diversification that

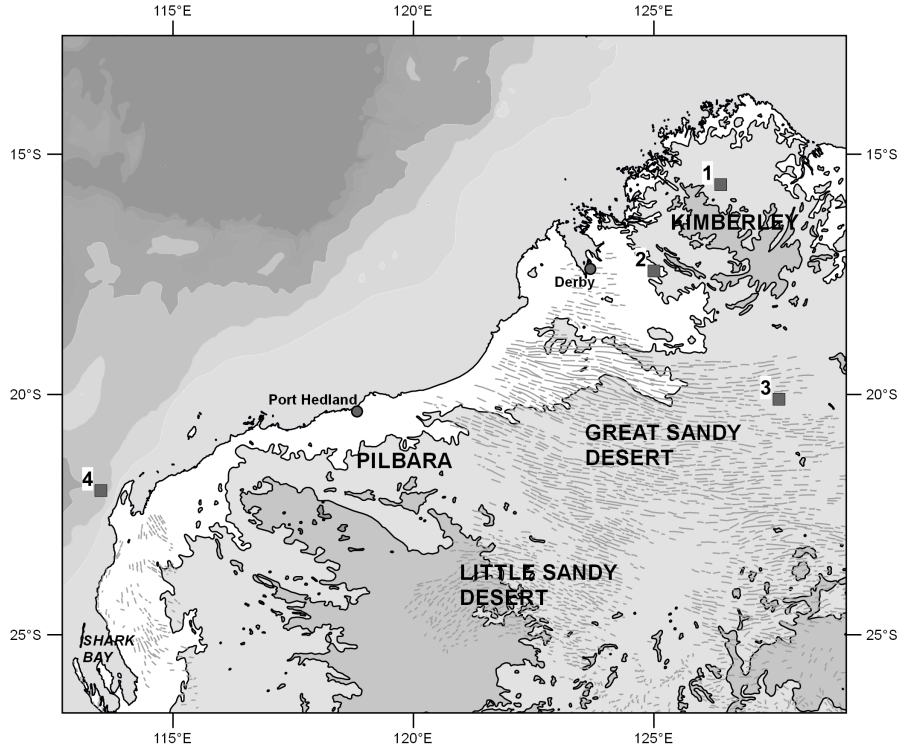

FIGURE A2.1: North-west Australia, showing places mentioned in the text. 1. Black Springs. 2. Carpenters Gap. 3. Lake Gregory. 4. GC17 pollen core.

has a long history as an environmental refugium (Pepper, Doughty and Keogh 2013 and references cited therein). For more than 20 years Australian archaeologists (e.g. Smith 2013; Veth 1989; Williams 2013) have advanced this theme when postulating how Aboriginal peoples adapted to extreme conditions during the Last Glacial Maximum. While, this matter will not be rehearsed further here, readers need to keep this special environmental circumstance in mind.

100,000 YEARS AGO

At about 100,000 years ago the north-west Pilbara coast area was humid and experienced high annual rainfall (300–400 mm). A summer monsoon was a prominent feature of the climate, producing from 95–355 mm of precipitation. The average winter rainfall (115 mm), was about 30% higher than today. Maximum and minimum temperatures were 29 °C and 18 °C,

respectively. Open eucalypt forests and woodlands, similar to vegetation patterns in the Kimberley today, appeared in north-west Pilbara coastal areas. Palms and ferns were also present, but limited to specific habitats.

Lake Gregory, situated well inland within the Great Sandy Desert dune fields, expanded at this time to about 1500–2000 km^2 (Bowler, Wyrwoll and Lu 2001). Major rainfall events in the lake's catchment, which extended into the eastern Kimberley, were frequent and quite substantial. The resulting groundwater recharge in the Lake Gregory region would have been significant.

80,000 YEARS AGO

The continental shelf became exposed to varying distances offshore from about 80,000 years ago. Sea levels continued to become lower until they began rising again some 70,000 years later (Reeves et al. 2008). The lowering of sea levels and exposure of the continental shelf during the Late Pleistocene created a new configuration of the Australian continent. Australia became linked with New Guinea about 70,000 years ago and Tasmania was joined to the mainland until about 14,000 years ago (Hiscock 2008, 21, Figure 7.1). Sahul and Greater Australia are the names commonly given to this continental land mass.

Grassland (*Cyperaceae, Asteraceae, Gramineae*) and eucalypt communities colonised the exposed shelf area off the present-day northern Pilbara coast (van der Kaars 1991). Lowland tropical forests occupied developing coastal areas, and fringe vegetation, mangroves and chenopod salt marsh species, existed but with a restricted distribution. The annual rainfall probably varied from 500 to 1000 mm.

The climate near the north-west Pilbara coast was less humid than before. Mean annual rainfall probably decreased by about 20% and the contribution from summer monsoons decreased by about a third. Temperature patterns remained mostly unchanged. There was a noticeable increase in *Callitris* (Cypress Pine), herbaceous groundcover and broadleaf grasses. Palms and ferns persisted in some areas.

Inland areas near Lake Gregory began experiencing dune-building activities sometime about 70,000 years ago, and the lake appears to have become dry (Bowler, Wyrwoll and Lu 2001).

65,000 YEARS AGO

Eucalypt forests still vegetated parts of the exposed shelf; however, grasslands began to expand and became the dominant vegetation community across the area. A lowland tropical forest still occupied emerging areas, and mangrove and chenopod salt marshes became the dominant fringing vegetation 65,000–53,000 years ago.

The pollen record from GC17 experienced an inexplicable hiatus 64,000–46,000 years ago. As well, no other palaeoenvironmental records are directly sourced for this period from other areas in north-west Australia. The most dramatic changes to the palaeoenvironment during this time were further receding of sea levels sufficient to expose the Arafura Plain that separated Australia and New Guinea. The Torres Strait also became dry land for a brief time (Reeves et al. 2008, Figure 10).

Palaeoenvironmental information from the GC17 core picks up again at about 45,000 years ago and continues to the present. Information from other sources in the area generally becomes plentiful. Significantly, this is the time marking the onset of human occupation of north-west Australia.

Environmental reconstructions presented below for more recent periods also draw on Reeves, Barrows et al. (2013) and Reeves, Bostock et al. (2013). These works are based on multi-sourced climatic data now available and are among the most informed and thorough contemporary reviews available. In particular, they form a comprehensive treatment of environmental change in tropical Australasia over the last 35,000 years. The timeframes referred to in these works and the Holocene subdivisions defined in Walker et al. (2012) are used as a rough guide for bracketing discussions that follow.

45,000 YEARS AGO

A transition to drier conditions occurred near the north-west Pilbara coast 46,000–40,000 years ago. Although annual precipitation in the area was much the same as at 65,000 years ago, the contributions of summer and winter rainfall were quite different. Summer precipitation totals almost halved on average to 65 mm. This represents the failure of summer monsoons, a pattern that persisted for roughly the next 30,000 years. Winter rainfall, on the other hand, roughly doubled and ranged from 85 to 217 mm. Humid

conditions continued, albeit to a lesser degree. Annual temperature patterns remained cool with the coldest time being from 43,000–39,000 years ago, when the lowest temperatures during the last 100,000 years became a regular occurrence. Vegetation patterns changed significantly. Open eucalypt woodlands were replaced by a mixed eucalypt and *Gyrostemon* shrubland, with an understorey of broadleaf grasses and herbaceous groundcover. Palms and ferns disappeared by this time.

Plant remains dating to around 40,000 years ago recovered from the Carpenter's Gap archaeology site in the Kimberley indicate this area was covered with grasslands similar to those in the area today (Wallis 2001). Fruit trees, *Terminalia* sp. and *Ampelocissus acetose*, and *Cyperaceae* sedges are also reported for the site (McConnell and O'Connor 1997). The occurrence of palm plant remains signals greater water availability and, probably, wet climatic conditions (see also Frawley and O'Connor 2010).

35,000 YEARS AGO

Sea levels dropped further to about 130 m below those today creating a broad coastal plain. By roughly 35,000 years ago the tropical lowland forest and eucalypt woodlands across the Sahul coastal plain began to diminish. Grassland communities began expanding across large parts of the exposed plain (van der Kaars 1991). The summer monsoon regime continued to fail, and the period from about 32,000–20,000 years ago marks the driest time during the last 100,000 years.

Climatic conditions in the north-west Pilbara coast continued to deteriorate and drier conditions set in about 32,000 years ago. Summer and winter rainfall decreased by about 20%. The occurrence of eucalypts, as well as other trees and shrubs, declined and herbaceous groundcover increased. Afterwards, until about 20,000 years ago, the vegetation of the north-west coastal areas resembled that found in the arid areas of the Pilbara today. Herb communities, daisies, grasses and salt-tolerant low shrubs or herbs, were common. *Gyrostemon* with some eucalypts persisted in the small tree and shrub layer (Williams et al. 2009), and was later largely replaced by *Callitris*. Hesse, Magee and van der Kaars (2004) postulate that the herbaceous vegetation along the north-west Pilbara coast contributed to reducing

dust plumes more than at other times, but in the Exmouth Gulf linear dunes developed from about the start of this period (Wyrwoll, Kendrick and Long 1993).

The Kimberley area became cooler and drier than during the previous period, and the area was vegetated with arid to semi-arid trees and grasses (e.g. *Panicum* sp.). Pockets of economically important fruiting trees (e.g. *Terminalia* spp.) were present, albeit probably restricted to moister vine thickets and gorges, where there were high seasonal water flows (Frawley and O'Connor 2010, 317). Around 33,000 years ago the Kimberley grasslands were less diverse, signalling a decrease in temperatures and rainfall (Wallis 2001).

Dune mobility in north-west Australia commenced about this time (Hesse, Magee and van der Kaars 2004). Linear desert dunes near Derby date between 32,000 and 10,000 years ago. Evidence from an offshore pollen core suggests substantial dune fields, comprising dust transported from the Great Sandy Desert, covered much of the exposed continental shelf for distances upwards of 1300 km north-west of the present-day stretch of coast from near Port Headland and the Kimberley, mostly in the area north of 18 °S latitude (Hesse, Magee and van der Kaars 2004, Figure 2). Dune building at Lake Gregory peaked 30,000–18,000 years ago.

25,000 YEARS AGO

The period from 25,000–15,000 years ago was the second coldest time during the last 100,000 years. The time referred to as the Last Glacial Maximum (LGM) is commonly dated to 22,000–18,000 years ago (Reeves, Barrows et al. 2013).

The tropical lowland forest and eucalypt woodlands diminished on the Sahul coastal plain, and grasses (e.g. *Gramineae*) and casuarina, which previously were a minor component of the woodlands, expanded to reach their maximum extent about 19,000–17,000 years ago (van der Kaars 1991). Windy conditions persisted throughout north-west Australia, and Great Sandy Desert dust plumes continued to support dune development in some areas of the exposed continental shelf (Hesse, Magee and van der Kaars 2004).

The vegetation near the North-west Cape remained open from 20,000–14,000 years ago and probably resembled that found on the Pilbara coastal plains today. The composition of vegetation communities, however, fluctuated markedly during this period. There were reductions in the occurrence of *Callitris* and daisies. Grasses, aquatic vegetation, trees and shrubs briefly increased before notably weakening. Chenopods, succulent herbs and low shrubs decreased. This pattern is thought to be indicative of rapid climatic change, a view in part supported by the rise and fall of sea surface temperatures (van der Kaars and De Deckker 2002). Dust sourced to the Gascoyne coastal plain was deposited in the North-west Cape area 24,000–16,000 years ago (Hesse and Tanish 2003). Rainfall varied between 160 and 410 mm, averaging about 305 mm. Summer rainfall improved, averaging about 95 mm, and winter precipitation was in the order of 105 mm, roughly 20% higher than that today. Both high and low temperatures differed from the previous period by only a few degrees, mean values 31 and 17 °C, respectively, roughly the same as those today.

The Kimberley too experienced an arid phase about 25,000 years ago. *Chenopodiaceae, Amaranthaceae, Cyperaceae* and perennial grasses (e.g. *Triodia* spp.) formed key components of the vegetation community (McConnell and O'Connor 1997). Around 18,000 years ago, the Kimberley, while remaining cool, experienced improved annual rainfall, averaging 250–500 mm (van der Kaars 1991). Grassland-shrubland vegetation communities shifted south and covered the area.

15,000 YEARS AGO

Climatic conditions began improving around 15,000–13,000 years ago, mostly as a result of the renewal of summer monsoons, which likely occurred in the north-west coastal Pilbara coast at this time (De Dekker, Barrows and Rogers 2014; Ishiwa et al. 2019; Kuhnt et al. 2015). This is attributed to rising sea levels, sea surface temperatures increasing by about 25% and the southward shift of the Intertropical Convergence Zone. Once the sea began to flood the continental shelf, grasslands gave way to extensive mangroves stands appearing on the newly developed mudflats. Chenopod communities vegetated tidal salt marshes. By 10,000 years ago eucalypt woodlands

recolonised areas closer to the present-day coast and lowland tropical forest occupied the banks of some waterways. Rainfall at this time was in the order of 500 mm per annum (van der Kaars 1991).

After 14,000 years ago, the climate of the north-west Pilbara coast experienced a marked upsurge in humidity. Average annual rainfall increased significantly and peaked at about 400 mm. Winter precipitation, in particular, was well above 100 mm. As a result, rain water run-off and groundwater accumulation increased and was sustained for long periods of time. *Cyperaceae* became considerably more abundant within the region's dryland shrub vegetation (Williams et al. 2009). Mangrove communities rapidly increased during two phases as sea levels rose, but then quickly declined once current sea levels were established. Saline mudflat species occupied this habitat afterward (Crowley 1996). Grasses and aquatic plants also expanded and open vegetation communities, comparable to those seen today on the Pilbara coastal plains, began appearing in the region.

Evidence from core U1461 dating from 11,500 and 8500 years ago demonstrates greater terrigenous sediments arriving on the current-day continental shelf (Ishiwa et al. 2019). This is attributed to the intensification of the summer monsoons and the concomitant increased erosion of the inland areas along the De Grey and Fortescue rivers.

In the Kimberley, the Late Pleistocene shrub and grasslands environment changed sometime just prior to 10,000 years ago (Frawley and O'Connor 2010), and vegetation communities common today began appearing. Among these, vine-thicket species (*Celtis philippensis* and *Trema tomentosa*) were present, thus indicating wetter environmental conditions. Boab and several species of fruiting trees (e.g. *Vitex glabrata* and *Terminalia* spp.), as well as sedges (*Cyperaceae*), occurred in the area. These changes are commonly attributed to the commencement of intense monsoon periods and these conditions continued to about the mid-Holocene. The establishment of the perennial Lake Mulan in the southern Kimberley is attributed to weather patterns during this period (Fitzsimmons et al. 2013).

Lake Gregory experienced another period of high-water conditions starting about 14,000 years ago, which is interpreted as support for resurgence of summer monsoon conditions (Hesse, Magee and van der Kaars 2004).

8000 YEARS AGO

Rainfall along the north-west Pilbara coast peaked between 8500 and 7000 years ago. This was followed by a general decline in annual precipitation and the progressive establishment of arid conditions by around 5000 years ago. Grasslands expanded and aquatic species became more prevalent, while *Callitris* began to decrease. Average annual rainfall was about 400 mm, with a range of 285–590 mm. Summer rainfall varied between 70–265 mm (average 140 mm), which was higher than at any time since around 80,000 years ago. Winter rainfall continued to decline with annual ranging between 0 and 170 mm (80 mm average). Mean annual temperatures peaked about 8,000 years ago, by which time maximum and minimum temperatures were 31 °C and 18 °C, respectively.

Hesse, Magee and van der Kaars (2004) noted that windier conditions returned to the north Pilbara coast about 5500 years ago, and coastal dune fields became active. Aeolian activities on the Gascoyne Plain likely were greatest during this time, peaking about 6000 years ago.

Lake Gregory levels continued rising and peaked about 6000 years ago (Fitzsimmons et al. 2013). This trend reversed around 5000 years ago and afterward the lake became increasingly ephemeral and progressively dried out with the weakening of the summer monsoon (Wyrwoll and Miller 2001).

5000 YEARS AGO

The climate of north-west Australia remained humid until around 4000 years ago, after which time drier conditions became well-established. Increased variability in the climate during this time presumably indicates the continuing lowering of sea surface temperatures and the onset of the El Niño Southern Oscillation (ENSO) (Reeves, Bostock et al. 2013). The contribution of ENSO to Pilbara rainfall patterns remains a matter of debate (O'Donnell et al. 2015; Williams et al. 2010).

Following stabilisation of sea levels, the environment along the north-west Pilbara coast began changing towards its present state. The decline of grasses (*Gramineae*) and aquatic vegetation communities, along with the upsurge of chenopod and amaranths, signalled an increase in arid conditions in the region. An open eucalypt shrubland also became well-established.

Temperatures moderated slightly from those in the preceding period and rainfall diminished, presumably as an outcome of declining sea surface temperatures. Annual falls averaged 380 mm, with a range of 275–551 mm. Summer rainfall varied between 5 and 160 mm, averaging 80 mm, while winter precipitation was 70–180 mm, with a mean of 130 mm.

The Kimberley region climate rapidly deteriorated from about 6000 years ago, as has been documented in the Black Springs pollen core (McGowan et al. 2012). Although there was a slight improvement with wetter conditions about 4600 years ago, the climate progressively worsened until about 1300 years ago, when wetter conditions returned. Dune fields along the Kimberley coast and about 100 km inland stabilised about 3000 years ago (Lees 1992). The climate continued to cool from those conditions present in the mid-Holocene.