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Causes and consequences of long-term climatic variability on the Australian continent

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SUMMARY

1. Ice-volume forced glacial–interglacial cyclicity is the major cause of global climate variation within the late Quaternary period. Within the Australian region, this variation is expressed predominantly as oscillations in moisture availability. Glacial periods were substantially drier than today with restricted distribution of mesic plant communities, shallow or ephemeral water bodies and extensive aeolian dune activity.
2. Superimposed on this cyclicity in Australia is a trend towards drier and/or more variable climates within the last 350 000 years. This trend may have been initiated by changes in atmospheric and ocean circulation resulting from Australia's continued movement into the Southeast Asian region and involving the onset or intensification of the El Niño-Southern Oscillation system and a reduction in summer monsoon activity.
3. Increased biomass burning, stemming originally from increased climatic variability and later enhanced by activities of indigenous people, resulted in a more open and sclerophyllous vegetation, increased salinity and a further reduction in water availability.
4. Past records combined with recent observations suggest that the degree of environmental variability will increase and the drying trend will be enhanced in the foreseeable future, regardless of the extent or nature of human intervention.

Keywords: Australia, biomass burning, climate variability, drought, Quaternary environments, vegetation history

Introduction

Australia is a continent with many unique elements that are considered, at least partially, to be the result of a generally dry climate and a high level of climatic and hydrological variability. Such conditions create great difficulties for the implementation of sustainable land management, especially at a time when predicted rapid climate change is superimposed on natural climatic variability and continuing high levels of human impact.

This paper provides evidence on late Quaternary climates in relation to ecosystem components, including people, to provide some basis for understanding the development and dynamics of present day landscapes and some prediction of future directions of change. It focuses on two recently constructed palynological records from climatic extremes in the northern part of the continent. Both records are derived from marine sediment cores providing continuous regional pictures of environmental change that are relatively well dated and can be related to global patterns of climate change. These marine records may be considered to be less relevant than those derived from swamps and lakes for understanding aquatic ecosystems in that they do not reveal specific details of changes in aquatic assemblages. However, records derived from aquatic basins on land are limited in that successional changes related to site development often override the imprints of both the climatic signal and regional water availability. In addition,

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conditions in the more arid parts of the continent are seldom conducive to the preservation of evidence that allows the production of continuous records, although some very useful proxy data have been obtained from the interior of the continent from sources other than pollen (e.g. Nanson, Price & Short, 1992; Bowler *et al.*, 1998). Some assessment of the status of aquatic ecosystems is possible from the transport of a quantity of sediment and contained pollen of riverine and swamp vegetation from adjacent rivers. The evidence from these marine records will be compared, where appropriate, with results from terrestrial sequences to provide a more comprehensive analysis of patterns and causes of change over the whole continent. The location of all studies mentioned is presented in Fig. 1, and all dates on sediment sequences have been standardised to calendar years.

The pollen sites

Cores from Site ODP 820 were collected by the Ocean Drilling Program, Leg 133, from beneath 280 m of water on the continental slope of northeast Queensland (16°36′S, 146°18′E). The site lies about 8 km outside the Barrier Reef and 30 km from land (Fig. 1). The majority of pollen is considered to have been transported by major rivers draining the heart of the humid Australian tropics (Kershaw, McKenzie & McMinn, 1993). That area is dominated by a variety of rainforest types which generally give way to *Eucalyptus*-dominated sclerophyll vegetation to the west, and to coastal grassy woodlands and swamps with common *Melaleuca* in poorly drained coastal lowlands. Mangroves fringe the mouths of estuaries. The region is dominated by southeasterly easterly trade winds that are a major source of high rainfall, in excess of 3000 mm on the coastal mountains and plains, which falls mainly in summer. This summer rainfall is supplemented by rain from cyclones and from the Australian monsoon, although this area is marginal to monsoon influence.

Core GC-17 was collected by the Franklin Fr10/95 cruise from the Exmouth Plateau at a water depth of 1093 m, some 60 km off the coast of northwestern Australia (22°02.74′S, 113°30.11′E). The adjacent land lies within the western coastal extension of the arid

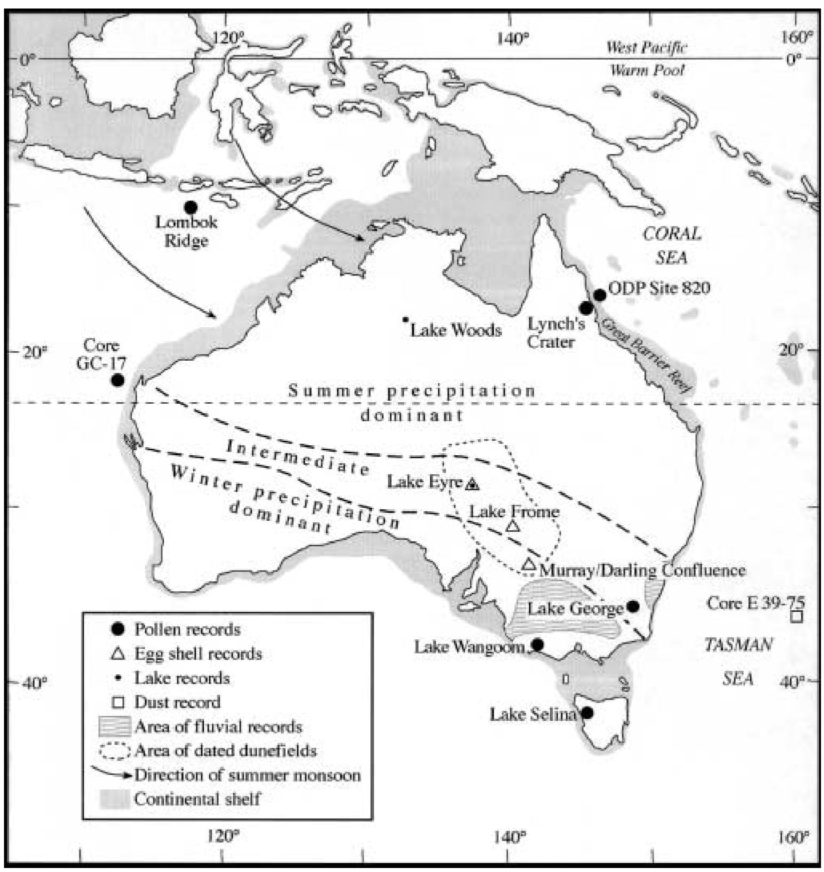

Fig. 1 Selected features of the Australian region including study areas and sites mentioned in the text.

continent interior and experiences a mean annual rainfall of about 200 mm. It is within the transition between monsoon-influenced areas to the north, where *Acacia* spp. and *Eucalyptus* spp. form open shrubland or woodland, respectively, above a hummock grass understorey, and westerly wind-belt influenced areas to the south dominated by *Acacia* shrubland. As a result, rain can be received in both summer and winter. Chenopodiaceae can be important components of the vegetation, and extensive areas of chenopodiaceous shrublands occur in coastal areas to the south of the site. Because of the lack of a coherent drainage system, it is more likely that pollen at the site is derived mainly by wind transport from the adjacent land.

Glacial–interglacial cyclicity

Minor changes in the distribution of incoming radiation to the Earth's atmosphere, as a result of variations in the earth's orbit or aspect with respect to the sun (Williams *et al*., 1998), have been considerd as the dominant control over global climate variation within the last million years or so. These variations have been amplified by the expansion and contraction of major ice sheets in the northern hemisphere and reflected globally in sea level variations. Changes are recorded in the oxygen isotopic composition of foraminifera preserved in marine records. These records show a similar pattern throughout the world's oceans and provide a basis for dating and correlation of Quaternary climates. The standardised marine oxygen isotope record through the last 500 000 years (Imbrie *et al*., 1984) is shown in Fig. 2 and can be compared with that derived from ODP Site 820 (Figs 2 and 3). Major oscillations dominated by the shape of the earth's orbit (eccentricity cycles) have a periodicity of about 100 000 years. Variations within these cycles are largely the result of the tilting of the earth's axis (obliquity) with a periodicity of about 40 000 years and precession of the equinoxes, with an average periodicity of about 20 000 years (Hays, Imbrie & Shackleton, 1976). For the purpose of this paper, odd numbered isotope stages (IS) can be regarded as interglacials, representing warmer periods with low ice volume and high sea levels (similar to modern conditions), while even numbered IS can be taken as cool glacial periods with low sea levels. The exception is the period IS-4 to IS-2 that represents the last glacial period, with IS-3 identified as a major interstadial phase.

The ODP pollen record, covering the last 250 000 years (Fig. 3), demonstrates dramatic changes in the vegetation of the humid tropics, much of which can be related to global forcing. In particular, mangrove values are high at times of major reductions in δ^{18} values, indicating substantial expansion of this vegetation type in association with marine transgressions. Grindrod, Moss & van der Kaars (1999) consider that features of the continental shelf landscape during transgressive phases were more important than rainfall in promoting mangrove expansion. There is also maximum expansion of complex rainforest, characterised by rainforest angiosperms, during interglacial periods, especially during the early parts of IS-7, the whole of IS-5 and IS-1 (the Holocene). Conversely, drier rainforest, dominated by conifers, particularly *Araucaria*, and/or open eucalypt woodland, have highest values during glacial periods. Clearly, interglacials produced regionally wetter conditions than glacial periods.

The much shorter record from the Exmouth Plateau (van der Kaars & De Deckker, 2002) shows less variation in pollen than ODP Site 820 with herb and small shrub vegetation dominant throughout the diagram (Fig. 4). Although *Acacia* forms the canopy of the majority of vegetation types, it has very low pollen representation due to poor dispersal ability. In this arid landscape, the vegetation appears to have been relatively insensitive to global scale climatic cyclicity. Apparently, the extent of eucalypt vegetation was lowest between *c*. 35 000 and 20 000 years ago, suggesting lowest rainfall towards the end of the last glacial period. Conversely, the higher Cyperaceae values in pollen zones GC7, GC2-1 and GC5 could indicate increased water availability during the interglacials of IS-5 and IS-1 and the early part of the IS-3 interstadial, respectively, with some support for higher moisture levels provided by fern spore representation towards the base and top of the record. Although the record is not firmly dated beyond the limit of radiocarbon dating, extrapolation of the timescale to the base of the sequence, together with available oxygen isotope data, suggests extension into the early part of IS-5 (van der Kaars & De Deckker, 2002). Mangrove vegetation is poorly represented, except for a marked expansion during the Pleistocene–Holocene marine transgression, as in ODP Site 820. The lack of any earlier mangrove response constrains the maximum age of the base of the sequence to IS-5.

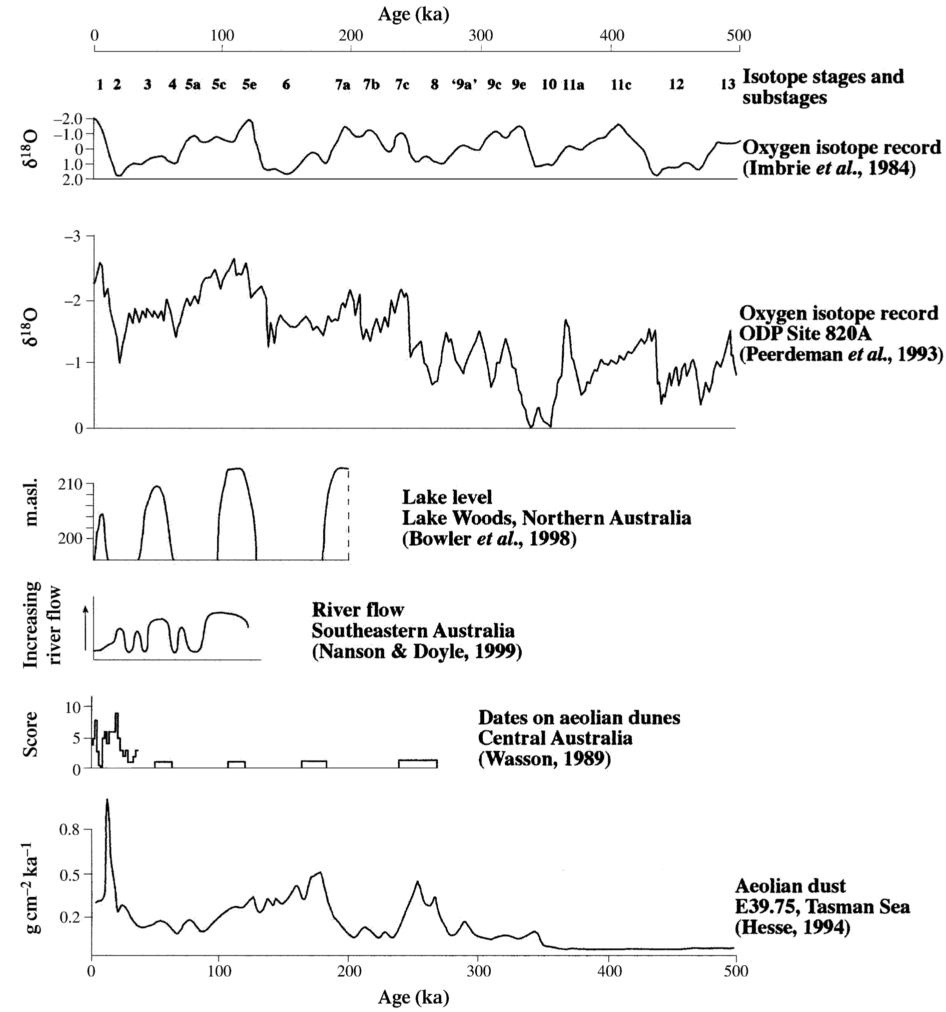

Fig. 2 Selected proxy records of environmental change in the late Quaternary of Australia in relation to the SPECMAP marine isotope record.

There is general continent-wide support for effectively wetter conditions during interglacial or interstadial periods than during glacial periods. Lake Woods in the Northern Territory (Fig. 2) was largely dry during glacials but covered a substantial area during the last interstadial and previous interglacials (Bowler *et al.*, 1998), a situation also evident at Lake Eyre (Croke, Magee & Wallensky, 1999). Rivers in southeastern Australia, including the River Murray (Nanson & Doyle, 1999), had substantially higher flows during the last interglacial and last interstadial than they did during intervening glacial phases (Fig. 2), while pollen records covering at least one to two glacial–interglacial cycles from this region [e.g. from Lake Wangoom on the Western Plains of Victoria (Harle, Kershaw & Heijnis, 1999) and Lake Selina in Tasmania (Colhoun *et al.*, 1999)] show predominantly grassland or steppe vegetation during glacial periods, which was replaced by forest during interglacials. The impact of aridity on the landscape, during glacial periods, is illustrated well by dates on mobile desert dunes and aeolian dust deposition from Australia in the Tasman Sea (Fig. 2), which indicate stronger winds and reduced vegetation cover associated mainly with glacial periods.

Late Quaternary trends

In contrast to the apparently stationary SPECMAP series (Imbrie *et al.*, 1984) (Fig. 2), all Australian records appear to show some trend towards drier

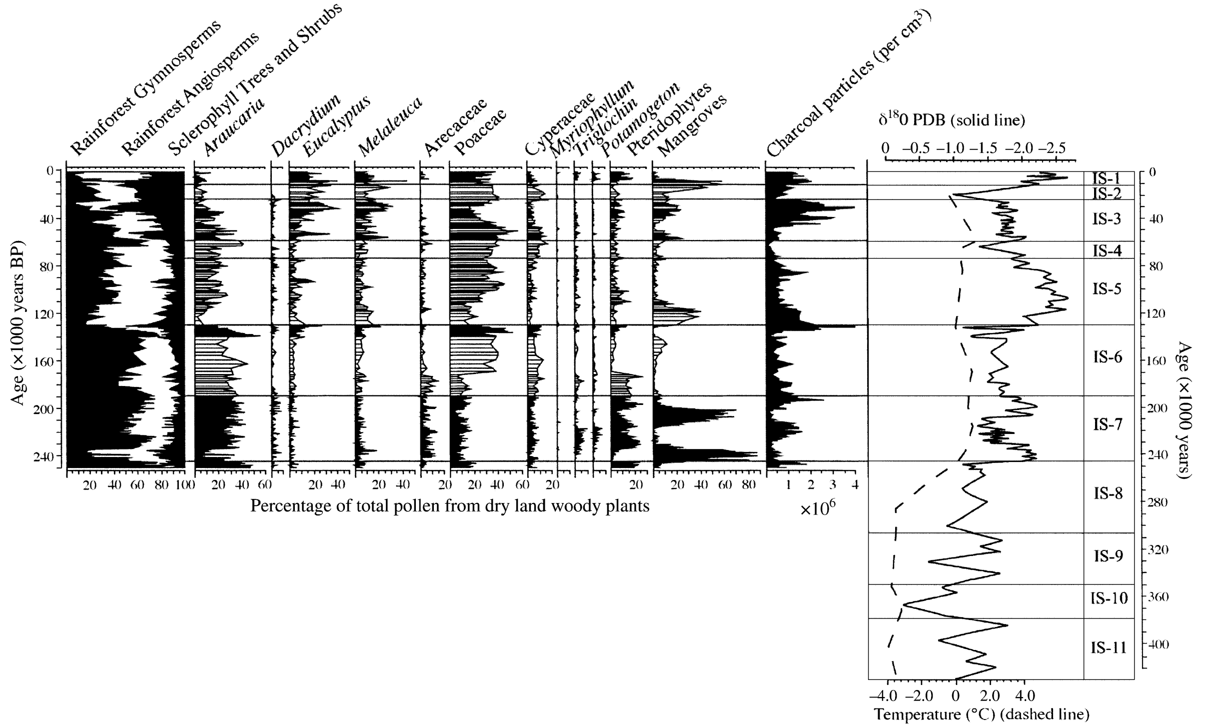

Fig. 3 Selected features of the palynological record from ODP Site 820 (Moss, 1999) in relation to the extended oxygen isotope and inferred sea surface temperature records from the same sediment core, and the marine isotope record. All pollen values are expressed as percentages of total pollen from dry land woody plants for the appropriate sample.

climatic conditions superimposed on glacial cyclicity through the late Quaternary. In progressive odd numbered isotope stages, the degree of lake filling and fluvial activity become reduced, while the evidence for aeolian activity increases during progressive glacial stages, with greatest aridity occurring at the very end of the last glacial period, incorporating the Last Glacial Maximum (LGM), between *c.* 27 000 and 17 000 years BP, and particularly within the Late Glacial period, *c.* 17 000–12 000 years BP (Kershaw & Nanson, 1993).

In the ODP 820 record, the trend is most marked by a general decline in drier araucarian forest elements, particularly *Araucaria*, and increase in sclerophyll components, especially *Eucalyptus* and *Melaleuca*. Within this trend, there are two major stepwise changes, one around the end of the IS-6 (*c.* 130 000 years BP), and the other towards the end of IS-3 (*c.* 36 000 BP), that correspond with highest charcoal peaks in the record and presumed highest levels of fire activity. Another abrupt change, without an associated charcoal peak, occurs in the earlier part of IS-6, *c.* 180 000 years BP. Here there are sustained declines in palms (Arecaceae) and ferns (Pteridophyta) and an increase in grasses (Poaceae). It is more likely that these changes are related, and may indicate a major replacement of fern and palm-dominated communities by grassland in the poorly drained coastal lowlands. An additional event involving aquatic or semi-aquatic vegetation is recorded *c.* 20 000 years ago, within the dry LGM, with the disappearance of the conifer *Dacrydium* from the record. Such a disappearance has been recorded in other pollen sites from northeast Queensland and the genus is no longer present anywhere in Australia. From the ecology of its nearest living relative, restricted to New Caledonia, it is considered to indicate a major decline in peat-forming forest, a type of aquatic ecosystem that may not be present today on the Australian continent (Bohte & Kershaw, 1999).

In Core GC-17, there is a sustained decline in *Eucalyptus* pollen *c.* 40 000 years ago, which is compensated for by an increase in Chenopodiaceae. At this time, there is a sharp decline in both the abundance and variability of charcoal, suggesting an associated change in fire regime. Although pollen of

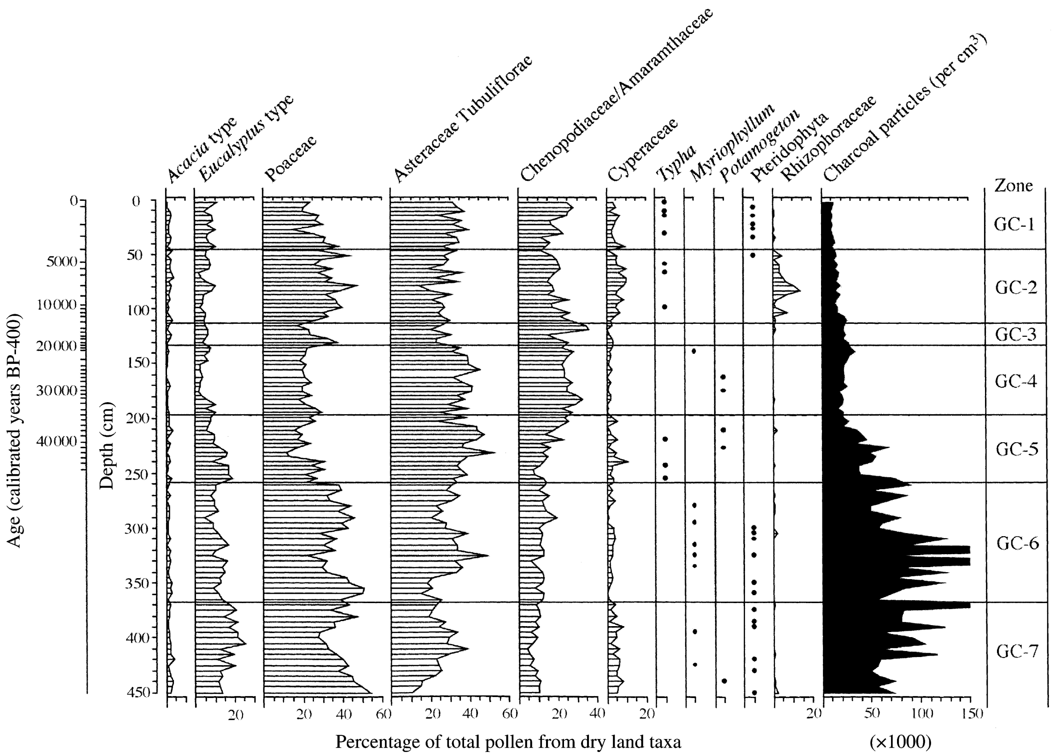

Fig. 4 Selected features of the palynological record from Core GC-17 (van der Kaars & De Deckker, 2002) in relation to a zonation produced by stratigraphically constrained numerical classification and a calibrated radiocarbon timescale. All pollen values are expressed as percentages of total pollen for the appropriate sample.

aquatic plants is poorly represented, apart perhaps from Cyperaceae, there appear to have been systematic changes in aquatic communities: *Myriophyllum* occurrences are largely restricted to the basal part of the sequence, *Typha* is restricted to the upper half of the record and *Potamogeton* covers the transition.

Causes of environmental trends

Several hypotheses have been proposed to explain the apparent drying trend in Australia. One is that it is the tail-end of changes associated with a global, late Cainozoic, climatic deterioration, which was sustained in Australia because of the continuing proliferation of fire-promoting sclerophyll vegetation dominated by *Eucalyptus* (Kershaw, 1994). However, emerging evidence about earlier parts of the Quaternary (e.g. Kershaw, Moss & Wild, in press; Wagstaff *et al.*, 2001) suggests that the late Quaternary is preceded by substantial periods of relative stability. From the evidence presented here, there has certainly been an expansion of eucalypt vegetation in northeastern Australia, but the abundance of eucalypts has actually been reduced in northwestern Australia.

A variant of this hypothesis is that the trend was promoted by increased amplitude of climatic oscillations with the switch from obliquity- to eccentricity-dominated cycles *c.* 800 000 years ago (Shackleton *et al.*, 1995). However, it is clear from the aeolian dust record (Fig. 2) that dust deposition, relating to glacial cyclicity, dates back only to *c.* 350 000 years ago. Evidence for desert dunes is evident only back to 250 000 years ago (Fig. 2), although this may be attributable to the detection limit of thermoluminescence, used to date these dunes. The coarse ODP 820 pollen sequence through the last 1.4 million years shows clearly that the observed trend in *Araucaria* pollen is restricted to the late Quaternary period (Kershaw *et al.*, 1993).

Another proposal has been that the arrival of people, with their use of fire, caused the transformation of the Australian landscape through promotion of sclerophyll vegetation at the expense of rainforest and other 'fire-sensitive' vegetation (Singh, Kershaw &

Clark, 1981). The suggestion from the pollen record of Lake George in southeastern Australia that impact dates from *c.* 125 000 years BP has always been unacceptable to the archaeological community as it substantially predates the artefactual evidence for the presence of people. Although a similar date to that at Lake George is recorded for the initiation of the decline in araucarian forest and high burning levels in the ODP Site 820 record, and a more comprehensive case for aboriginal burning has been made on this and other evidence (Kershaw, Moss & van der Kaars, 1997), the lack of archaeological support continues to make an early people explanation extremely speculative. However, there is a good possibility that people did impact the environment at later times and this aspect is examined as a component of other hypotheses.

A key to understanding the late Quaternary environmental trend may be the systematic shift in oxygen isotopes from ODP Site 820 that occurs between *c.* 400 000 and 250 000 years BP (Peerdeman, Davies & Chivas, 1993). This shift is interpreted as an increase in sea surface temperatures of 4 °C (Fig. 3), and is consistent with sedimentological evidence from the ODP core of the initiation of the Great Barrier Reef (Davies, 1992). Such a temperature increase may relate to the initiation or expansion of the West Pacific Warm Pool (WPWP), centred to the north of this area, which is the warmest ocean water on earth. The major climatic significance of the WPWP is that its presence is critical to the establishment of the sea surface temperature gradient across the Pacific Ocean, considered to be a necessary prerequisite for the operation of El Niño-Southern Oscillation (ENSO) climatic variability (Godfrey, 1996). It is hypothesised that the northward drift of Australia into Southeast Asia progressively focused the passage of warm water from the Pacific to the Indian Ocean between the two continents, as part of the global thermohaline oceanic circulation system (Godfrey, 1996), into narrower straits. It is possible that a threshold was reached *c.* 400 000 years ago when the straits became too narrow to transport all this warm water that then accumulated as the WPWP.

In relation to the ODP Site 820 pollen record, droughts associated with dry El Niño phases of ENSO are considered to have promoted fires and facilitated the replacement of drier rainforest by sclerophyll vegetation. The pattern of change in terrestrial vegetation might be explained by variation in intensity of ENSO operation, in association with other forcing factors, as ENSO changed its level of activity in the Holocene (McGlone, Kershaw & Markgraf, 1992) and postulated, based on results of climate modelling (Clement, Seager & Cane, 1999), to have varied on longer timescales. Spectral analysis of components of the ODP palaeoecological record has shown that, in contrast to the predominant influence of orbital forcing on oxygen isotope and most pollen component curves, both charcoal and araucarian forest components have a dominant 30 000 year periodicity. This could be an ENSO activity frequency (Kershaw, van der Kaars & Moss, in press). The sustained changes *c.* 130 000 years BP might then be explained by the correspondence of high ENSO activity and particularly dry conditions at the height of the IS-6 glacial, while those culminating *c.* 36 000 years BP, where there is no evidence for major climate change, could be explained by a combination of the presence of people and high ENSO activity.

There are no charcoal peaks associated with changes in poorly drained environments. It is possible that frequent droughts alone may have promoted changes in the coastal lowlands *c.* 180 000 years ago, although altered drainage patterns and hence vegetation changes indicated in the pollen record, particularly with the development of the Great Barrier reef system, provides an alternative, and perhaps equally unconvincing, explanation. There is, however, a sustained and unexplained major increase in Poaceae pollen around this time within a similarly long marine record from the region, Lombok Ridge, north off the northwestern part of Australia (Wang *et al.*, 1999). In the case of the decline of peat-forming forests, continued human impact and dry conditions at the height of the LGM may have been the critical combination.

The degree to which this general scenario can be applied to the whole of Australia is debatable, as in some areas, particularly the western part of the continent, the impact of ENSO is limited. However, the Core GC-17 record clearly shows vegetation change within IS-3, *c.* 40 000 years ago. Here, it may be argued that, even within this arid landscape, the initiation of aboriginal burning was the basic cause. Under these circumstances, however, is it more likely that increased burning activity would have resulted in a reduction in eucalypt representation and a decrease in charcoal abundance, the opposite to proposed patterns in northeastern Australia? Perhaps a feasible explanation is that a change from occasional high intensity burns to a 'managed' regime of low intensity frequent fires reduced both the amount and variability of charcoal being dispersed to the marine site. Alternatively, the reduction in fire intensity could have been related to a depletion of flammable material in the landscape.

An interesting interpretation of environmental change occurring at a similar time to that in northwestern Australia and in similarly arid environments, has been proposed from an examination of fossil eggshells of flightless birds preserved in aeolian dune systems of southeastern Australia (sites shown in Fig. 1). Miller *et al.* (1999) and Johnson *et al.* (1999) hypothesise that a change in the isotopic composition of *Dromaius* (emu) egg shells *c.* 50 000–45 000 years ago demonstrates a change in the bird's diet resulting from a reduction in shrub cover. This vegetation change, which they attribute to aboriginal burning on the basis of the lack of evidence for global climate change at this time, also resulted in the extinction of the other recorded flightless bird, *Genyornis*. This latter bird, being a browser, was unable to adapt to the changed vegetation cover. They further suggest that the opening up of the vegetation through aboriginal burning resulted in reduced moisture interactions between atmosphere and vegetation and consequently a decrease in effectiveness of summer monsoon penetration into the centre of Australia.

This model is effective in explaining why water was more abundant in the interior of Australia during interglacials previous to the Holocene, and may provide a more comprehensive explanation for sustained changes in the Core GC-17 record. However, Core GC-17 is recording changes in coastal rather than inland vegetation, so that the influence of vegetation on inland penetration of the monsoon is not a factor. It could be that there has been a general decrease in effectiveness of the Australian monsoon through the last few hundred thousand years. Such a decrease would be consistent with the development and increase in intensity of ENSO variability through observed linkages between the two systems within the period of instrumental records (e.g. Webster *et al.*, 1998).

Implications for the future

The prognosis for the future is not optimistic. Climate has been the major force driving a long-term trend towards a drier and more variable environment with associated increases in sclerophyllous and saline vegetation and a reduction in freshwater ecosystems. Australian people have only a secondary influence on the creation of this environment and probably can do little to reverse the trend. The impact of a suggested 4 °C temperature increase in sea surface temperatures several hundred thousand years ago appears to have been environmentally disastrous. The possibility of a future rise of similar magnitude through enhanced greenhouse warming is expected to exacerbate environmental problems, if the intensity and impact of recent El Niño-induced droughts (e.g. Goldammer, 1999) are any guide.

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