The palaeoceanography of the Leeuwin Current: implications for a future world

K-H Wyrwoll[1], B J Greenstein[2], G W Kendrick[1,3] & G S Chen[4,5,6]

[1] School of Earth and Environment, The University of Western Australia,
35 Stirling Highway, Crawley WA 6009
✉ wyrwoll@segs.uwa.edu.au

[2] Department of Geology, Cornell College, Iowa 52314 USA.
✉ BGreenstein@cornellcollege.edu

[3] Department of Earth and Planetary Sciences, Western Australian Museum,
Locked Bag 49, Welshpool DC, WA 6986

[4] Institute of Earth Environment, Chinese Academy of Sciences,
Xi'an, China.

[5] Graduate School of Chinese Academy of Sciences, Beijing, China.

[6] Center for Climatic Research, University of Wisconsin,
Madison, USA.
✉ chengs@ieecas.cn

Manuscript received July 2008 accepted; March 2009

Abstract

Long-term progressive changes of the Leeuwin Current are linked to plate and ocean basin 'geography' and Cenozoic global climates and palaeoceanography. Suggestions of the presence of a proto-Leeuwin Current as early as late Middle to Late Eocene times (c. 35–42 Ma) cannot be verified by the fossil record of the western margin of Australia. "Leeuwin Current style" circulation around Australia was certainly established by the early Oligocene, in response to palaeogeographic changes in the Tasman Strait. This, followed by tectonic reorganisation of the Indonesian Archipelago throughout the Miocene, provided a palaeogeographic setting, which by the Pliocene was essentially that of today. The subsequent history of the Leeuwin Current comprises climatically-induced changes operating over orbital and sub-orbital temporal scales. Specifically, the advent of Pleistocene-style climates, especially over the last 800 000 years, and their associated interglacial – glacial states provide the two end-member climate-ocean states that have characterised Leeuwin Current activity during that time. Indications of the nature of these contrasting states is provided by: (i) the Last Interglacial (c. 125 Ka) during which sea level was higher by some +4 m, and with higher sea surface temperatures (SSTs) clearly indicating a more 'active' Leeuwin Current; and (ii) the Last Glacial Maximum (21 Ka), during which sea level was some 130 m lower than today, resulting in massive shelf extensions along the coast of Western Australia, accompanied by reduced Indonesian Throughflow, lower low latitude SSTs and changes in the Western Pacific Warm Water Pool, and with these changes, possibly reduced Leeuwin Current activity. Sub-orbital scale fluctuations in current strength are driven by global climate change associated with El Niño – La Niña events as well as regional climatic changes driven by volcanism. These forcing mechanisms operate at time scales well within the reach of human experience, and provide important comparative data for predicting the response of the Leeuwin Current to climate change predicted for this century. Studies of the impact of changes in the vigour of the Leeuwin Current on shallow marine communities are in their infancy. Coupling climate models with geological analogues provide important research agenda for predicting the trajectory of future changes to the Leeuwin Current and their impacts on the marine biota of coastal Western Australia.

Keywords: palaeoceanography, Leeuwin Current, Last Interglacial, Last Glacial Maximum

Introduction

The geological history of the Leeuwin Current involves a combination of re-arrangements of global geography in terms of both the continent positions and associated plate tectonic changes, and a global climate regime which brought the Earth out of an essentially 'ice

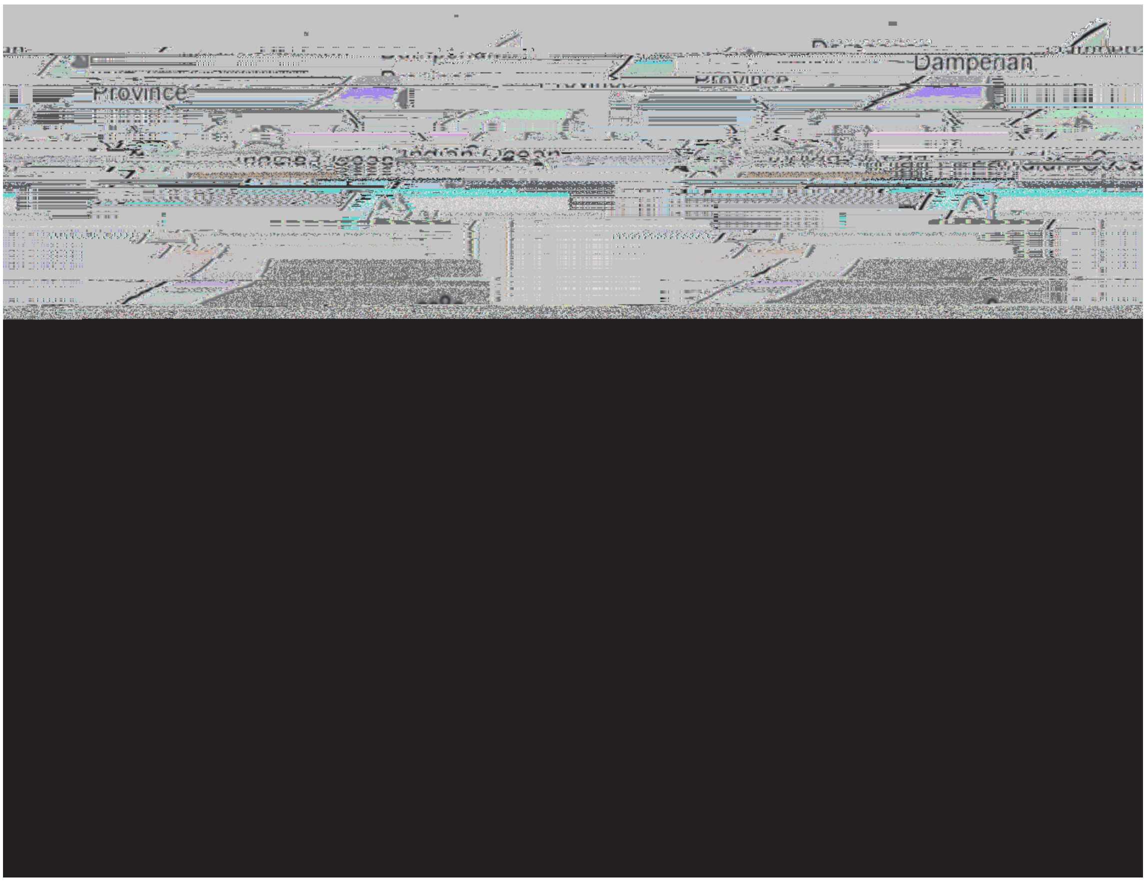
comparable faunas are known from either the Perth or Bremer Basins but the Colville Sandstone of the marginal Eucla Basin (equivalent to the Nullarbor Limestone (Lowry 1968, 1970)) provides comparative evidence from the south coast for that time.

Current, to be firmly established during Pleistocene times and continuing today.

Leeuwin Current activity over orbital time scales – the last *c.* 2 million Years

Once the terrain arrangement north of Australia resembled that of the present, the details of global climate dynamics became the sole drivers of Leeuwin Current events. Over the time scales of the last c. three million years, the Earth attained a full expression of the present ice age. Of special relevance is that during the last 1.75

Mollusc assemblages of the Ascot Formation are extensive but largely unrecorded beyond the limited listing of taxa in Kendrick *et al.* (1991) but, compared with that of the Roe Calcarenite, are clearly younger, include a distinct endemic element and are deficient, rich limestone bar, once located between Rous Head and Arthur's Head and removed during construction of the



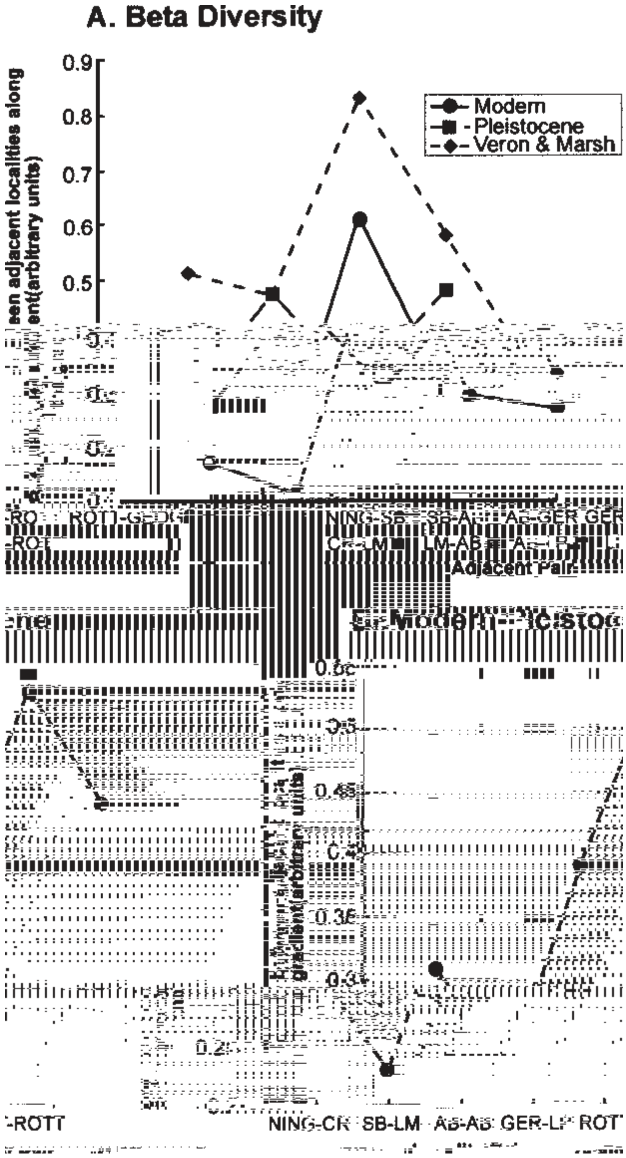


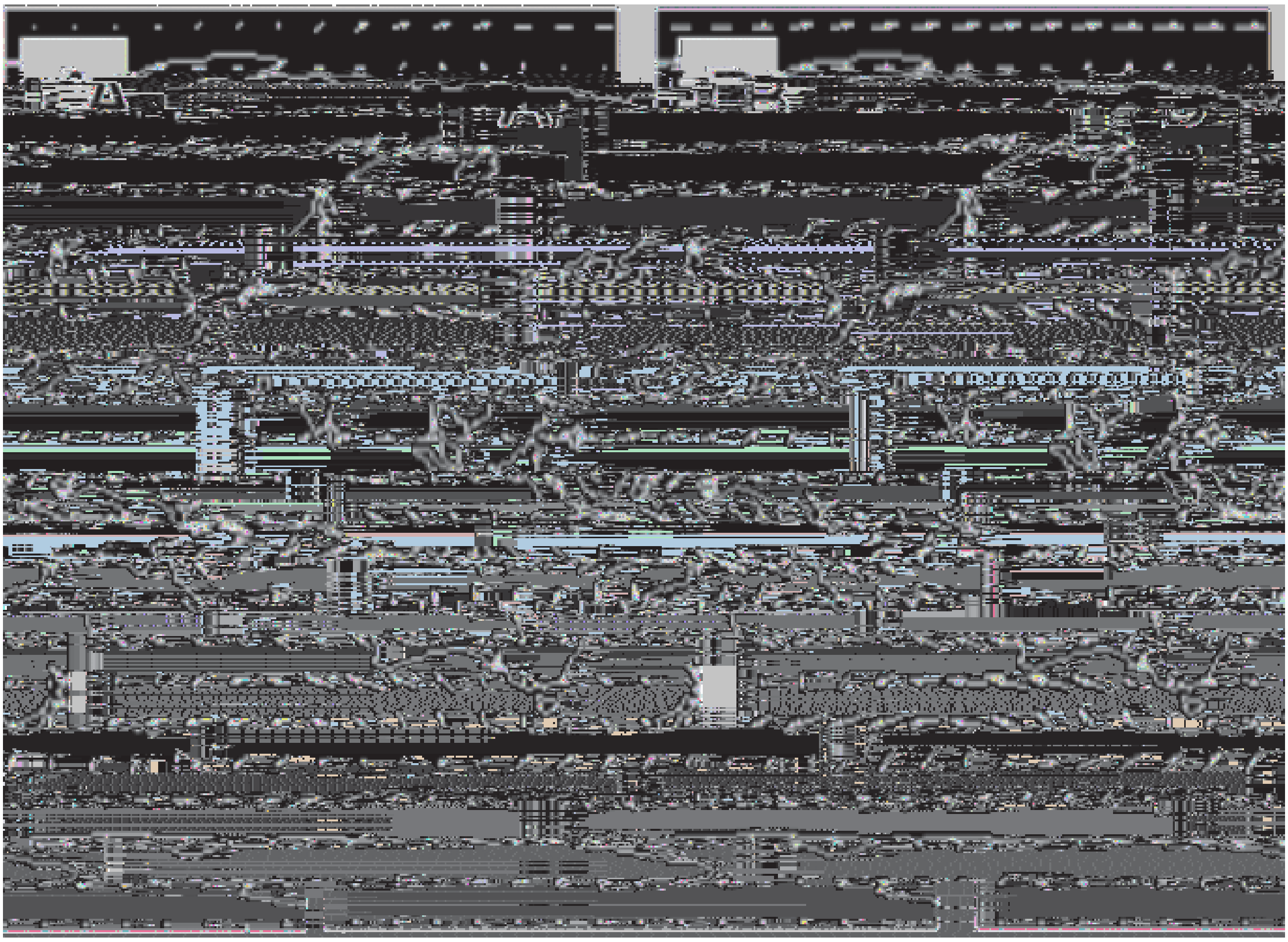
Figure 3.

suggesting that during Last Interglacial summers the Leeuwin Current was more intense and delivered a larger volume of warm water to the southern coast of Western Australia. They draw attention to a modern analogue, the high latitude reefs of southern Japan, where coral calcification occurs mainly in the summer months in response to the warm Kuroshio Current. Additionally, McCulloch & Esat (2000) were unable to provide a reliable age for the coral analysed but associated it with an assemblage dated at 128–122 Ka.

There are other claims of varying SSTs during the Last Interglacial. Wells & Wells (1994) in their reconstruction of the ocean circulation off Western Australia indicate a significant reduction in SSTs at 130 Ka. They suggest that at 120 kyrs, winter SSTs off the North West Cape were 3°C higher than at present, with a 'pool' of colder water to the west. In adopting this inference, it needs to be recognised that the SSTs of Wells and Wells tend to underestimate SST (Barrows et al. 2000). On the basis of ^{23}U – ^{230}Th ages, Stirling et al. (1998) concluded that coral growth associated with a Last Interglacial sea level high stand along the Western Australia margin spans the period c. 128–121 Ka, seeing this as a period of reef growth after which reef growth was arrested due to lower SSTs. They considered two alternate, though not mutually exclusive possibilities: (i) reef termination may have been related to a sudden switching off of the Leeuwin Current at c.121 Ka, a consequence of global climate events; (ii) the absence of coral reefs may simply be due to a more oscillating sea level history after c. 121 Ka, preventing reef growth. However, in the Houtman Abrolhos a coral reef fringe is preserved in a sheltered location in the Wallabi Group and has been dated to 117–116 Ka (Zhu et al. 1993). Furthermore, in cores from the Ningaloo reef barrier there is clear evidence of coral growth until c. 115±2 Ka (Collins et al. 2003). At least for these areas, the indications are that reef growth may not have been constrained by lower SSTs during the later part of the Last Interglacial.

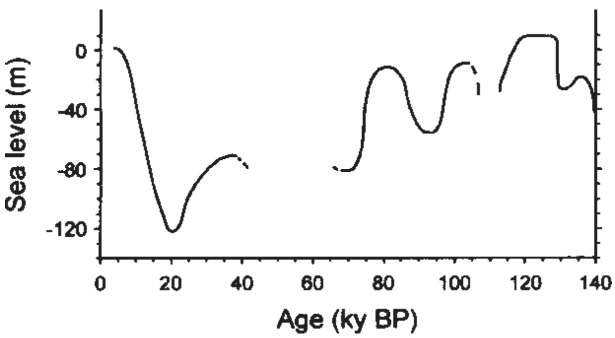
In summary, it is clear that our understanding of Last Interglacial events, both in terms of sea level changes and likely differences in SSTs, is incomplete. Nevertheless it can be confidently concluded that the palaeoecological data from southwestern Australia indicate a stronger than present Leeuwin Current during at least part of the Last Interglacial. If we follow the argument of Stirling et al. (1998) that coral growth (at least for the region south of the Houtman Abrolhos) spans the period c. 128–121 Ka, and that subsequently reef growth was arrested due to lower sea surface temperatures, recent general circulation experiments allow an exploration of the mechanisms by which this occurred.

Wyrwoll &Valdes (2003) undertook a sensitivity experiment to establish the response of the northwest Australian monsoon to a precession driven, high insolation event that characterised the low latitudes of the Southern Hemisphere at 115 Ka. The sensitivity experiment used the high resolution Hadley Center climate model – HadAM3 version of the U.K. Meteorological Office's Unified Model (Pope et al. 2000). One result of the experiment showed a significant increase in lower tropospheric southerly winds along the coast of Western Australia during March (Figure 4). In light of the fact that the Leeuwin Current is controlled by the balance between a southward pressure gradient force and a northward wind stress, this could relate to reduced Leeuwin Current activity during the later part of the Last Interglacial. However, why a stronger Leeuwin Current existed at other times during the Last Interglacial, remains an open question.



Sea level and Leeuwin Current events during the Late Pleistocene

Figure 5 provides a detailed sea level history from the Last Interglacial to the present. It is clear that for much of this time sea level was lower than present. Consequently, only evidence recovered from ocean cores exists, and even that is very limited. Rivers *et al.* (2007) suggested that there is evidence during Marine Isotope Stage 3 (MIS 3) (*c.* 30–60 Ka) for the presence of a warm-water current



in the Great Australian Bight, and relate this to the Leeuwin Current. Takahashi (2000) recognises a weakening of the Leeuwin Current during the end of MIS 3.

The Last Glacial Maximum

Because it marks the nadir of the last glacial, the Last Glacial Maximum (LGM), *c.* 21 Ka, provides a profound contrast to the Last Interglacial, prompting interest in the status of the Leeuwin Current at that time. Massive global-scale reorganisation of both atmospheric and oceanic circulations characterised the LGM, with sea levels some 130 m lower than at present. With the lowering of sea level, a massive extension of the land area of Western Australia occurred and with it, major changes in the Indonesian Archipelago (Figure 6). In

on the state of the Leeuwin Current during the LGM. An overview of the eastern Indian Ocean circulation and

provide details of the variation of ENSO occurrence during the Holocene. They recognise 12 events/century for the period 7.6–7.1 Ka; 8 events/century for the period, 6.1–5.4 Ka; and 6 events/century at 6.5 Ka. During 2.5–1.7 Ka, the coral records indicate large and protracted δ^{1} O anomalies indicative of particularly severe El Niño events. They note specifically, that the 2.5 Ka Madang Papua New Guinea corals record a protracted 4-year El Niño, like the 1991–1994 event, but almost twice the amplitude of the 1997–1998 event (Tudhope *et al.*2001). In addition, they recognise that the 2 Ka Muschu Island (Papua New Guinea) coral δ^{1} O record shows a severe 7 year El Niño, longer than any recorded Holocene or modern event. This is supported by the findings of Woodroffe *et al.* (2003) who analysed a late Holocene coral record from Christmas Island (central Pacific) and found evidence for an extreme El Niño that was twice the amplitude of the 1997–1998 event. Significant variations are also evident in the more recent historical record (*e.g.*, Allan *et al.* 1996). Given the strong and

Bernasconi S M, Andres M S & McKenzie J A 2002 850,000-year record of sea -level fluctuations and margin evolution from Great Australian Bight, Site 1127, ODP Leg 182. American Geophysical Union, Fall Meeting, Abstract #PP12A-0327.

Beu A G 2006 Marine molluscs of oxygen isotope stages of the last 2 million years in New Zealand. Part 2. Biostratigraphically useful and new Pliocene to Recent bivalves. Royal Society of New Zealand 36: 151–338.

Beu A G & Darragh T A 2001 Revision of southern Australia Cenozoic fossil Pectinidae (Mollusca : Bivalvia). Transactions of the Royal Society of Victoria 113: 1–205.

Bradley R S 1999 Paleoclimatology: reconstructing climates of the Quaternary. Academic Press, London.

Cane M A 2005 The evolution of El Niño, past and future. Earth and Planetary Science Letters 230: 227–240.

Cane M A & Molnar P 2001 Closing of the Indonesian seaway as a precursor to east African aridification around 3–4 million years ago. Nature 411: 157–162.

Clement A C, Seager R & Cane M A 2000 Suppression of El Niño during the mid-Holocene by changes in the Earth's orbit. Paleoceanography 15: 731–737.

Cole J 1996 Coral records of climate change: understanding past variability in the tropical ocean-atmosphere.