Geological Setting, Marine Geomorphology, Sediments and Oceanic Shoals Growth History of the Kimberley Region

L B Collins

Department of Applied Geology, Curtin University,
GPO Box U1987, Perth WA 6845
✉ L.Collins@curtin.edu.au

Abstract

The offshore sedimentary basins of the Kimberley region are becoming established as a major hydrocarbon province, but the region is also known for its marine wilderness values. Its position close to a plate boundary is reflected in significant rates of continental margin subsidence. In addition to the "normal" continental margin geomorphic units of shelf, slope and rise the offshore Kimberley region has well developed plateaux (*e.g.* Scott Plateau), terraces (*e.g.* Rowley Terrace), and banks (*e.g.* Sahul rise, Sahul bank) which interrupt the otherwise gentle seaward slopes present, and provide foundations for the offshore reefs, including the Sahul shoals, Ashmore, Seringapatam, and Scott Reef and the Rowley Shoals. The continental shelf is a vast low gradient ramp with sandy bioclastic sediments reflecting both the modern biota and a history of past sea level and oceanographic changes, so that sediments are a mixture of modern bioclasts, particles stranded by sea level rise, and precipitated carbonate grains (ooids and peloids) which were dominant prior to Leeuwin Current onset some 12,000 years ago. Whilst little is known about the nearshore fringing reefs, in areas of macro-tides and significant sediment input, the morphology, internal architecture and growth history of reefs and shoals of the Oceanic Shoals Bioregion indicates that these are long-lived features which have survived despite relatively high rates of continental margin subsidence and oscillating sea levels of the Pleistocene glaciations. However, drowning by sea level rise was the fate of some of the reefs and shoals of the Sahul Shelf, situated at the leading edge of the downturning Australian Plate, in contrast to continuing reef growth at Scott Reef and the Rowley Shoals to the south. In the morphological series provided by the three Rowley Shoals, differential subsidence is the primary control on rates of lagoon infill controlling platform morphology. This study demonstrates the resilience of reefs on the subsiding margin whilst linking reef morphology to the relative amount of pre-Holocene subsidence.

Keywords: geomorphology, Kimberley, continental shelf, sediments, Oceanic Shoals Bioregion, coral reefs, sea levels, growth history, subsidence

Introduction

The remote Kimberley Region in north Western Australia has a deeply embayed tropical macrotidal coast fringing an onshore complex of Proterozoic rocks known as the Kimberley Basin, which is bordered by Phanerozoic sedimentary basins (Fig. 1). Whilst the marine realm is essentially a wilderness region there are significant discoveries of hydrocarbons offshore, and this is driving the development of the petroleum industry with several fields discovered and offshore gas developments foreshadowed. The offshore and onshore infrastructure requirements of these activities will have impacts in both terrestrial and marine environments, and this new phase of activities has already commenced. Recently we have seen a major oil spill at the Montara wellsite, an ongoing land use and heritage dispute over the proposed gas hub site at James Price Point, and newly declared marine and terrestrial parks in the region.

The purpose of this paper is to provide some of the geological and geomorphological framework which is relevant to the region and its biodiversity, with particular reference to the remarkable offshore reef systems which characterise the outer parts of the continental shelf, close to some of the hydrocarbon discoveries.

The continental shelf and margin are in the domain of the Indian South Equatorial Current. It is situated in a tropical marine realm, with warm temperatures between 26–28 °C, and lower salinity (34.5 to 35.7) that characterises the waters in the proximity of the Indonesian Throughflow. Offshore areas have clear waters due to low nutrient levels and no continental sediment input, because of distance from the coast, providing an ideal environment for the development of coral reef communities. The proximity to the Indonesian Throughflow has been shown to increase the importance of both Pacific and Asian reef species southward, and the Leeuwin Current, which flows southwards against the prevailing equatorward winds, is an important control on larval delivery, whilst suppressing upwelling along its path (Fang & Morrow 2003). The North West Shelf is tidally dominated, with coastal mean spring range increasing from 1.7 m at Exmouth to 9.2 m in King Sound (Harris *et al.* 1991). Both Scott Reef and Rowley Shoals have semi-diurnal tides with a tidal range of 4.1 and 4.5 m respectively (National Tidal Center 2009a, b; meso-
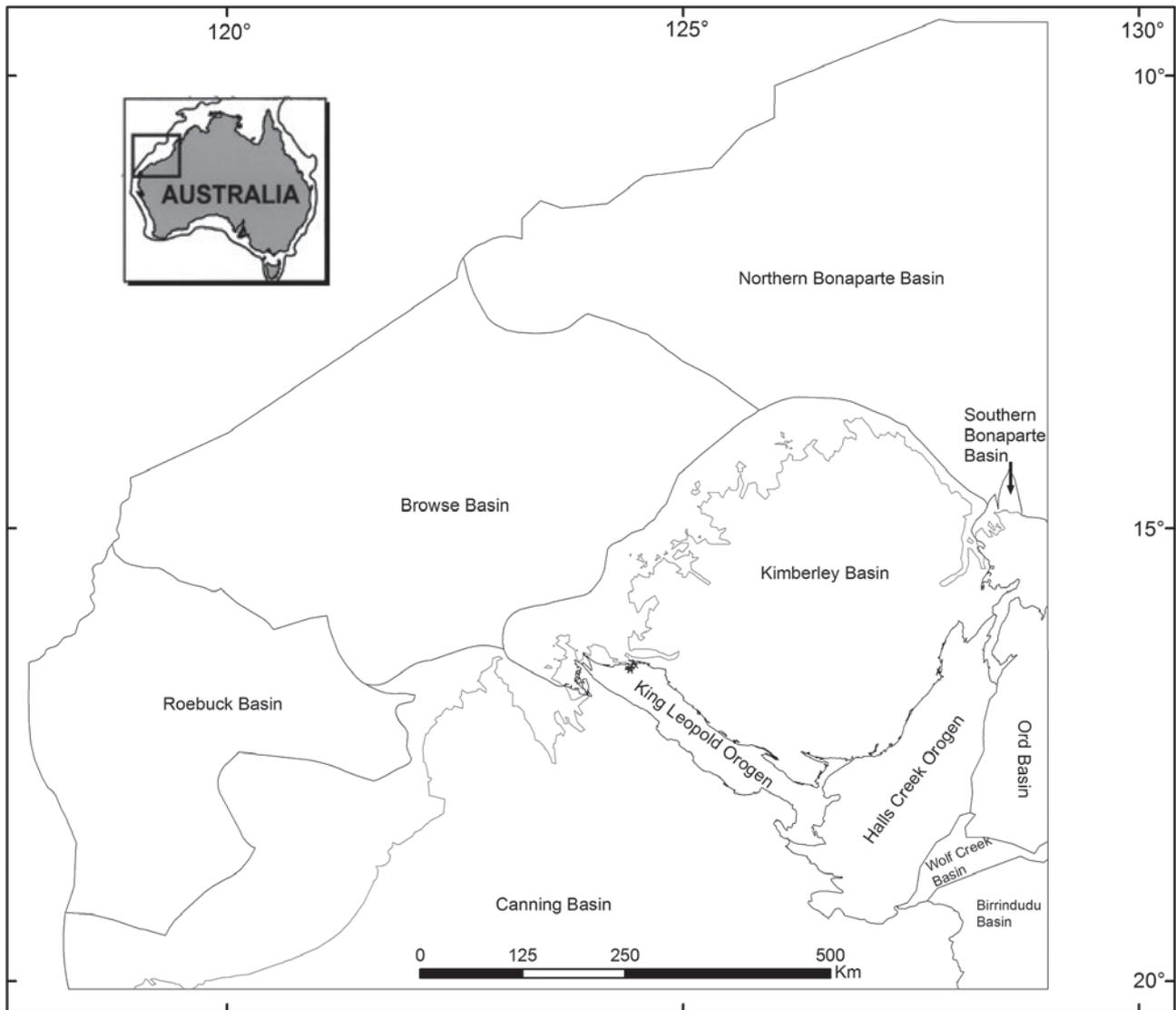
Figure 1. Onshore geological elements and sedimentary basins of the Kimberley region

high tidal range, *sensu* Hayes 1975). The region lies in the monsoonal belt with prevailing westerly or northwesterly rain-bearing winds from November–March, and dry southeasterly or easterly trade winds from May to September. The region is cyclone-influenced (average 3 per year, Lough 1998) and has southwest prevailing swell.

Methods

Background information on geology, geomorphology and bioregions was acquired from various sources referred to in the text. Shelf sediment mapping (by James, Bone and Collins) is summarised from James *et al.,* (2004). Offshore field surveys were carried out using the CSIRO research vessel RV Franklin during Voyage FRO5/00, for collection of seafloor samples, bathymetric profiles, and shallow seismic data. Both shipboard and small vessel seismic surveys were conducted using an ORE Model 581 3A Acoustic Source (Boomer), driven by a Geopulse 5420A power supply. A Benthos multi-element streamer

was used for small vessel work and a Teledyne 4 channel streamer was used for *Franklin* work. The seismic acquisition system used was a Geoacoustics SE88 1 Sonar Enhancement System, and a Garmin GPS unit supplied GPS data to the acquisition system on the small vessel. *Franklin* DGPS data were supplied and processed by Navipac software for onboard seismic acquisition.
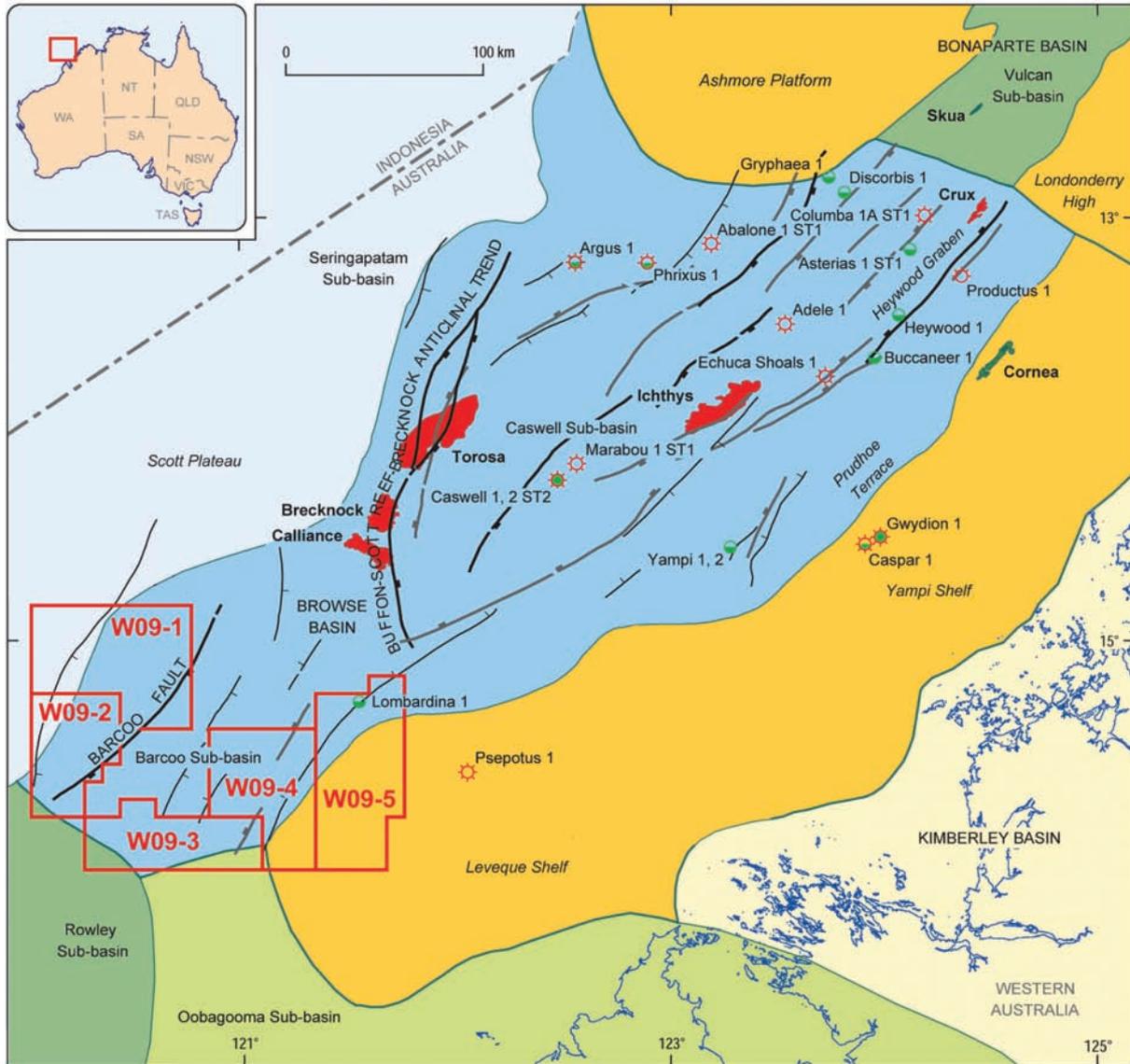
Oceanographic data were acquired using CTD and bathymetric data by PDR (Precision Depth Recorder). Geological sampling was by Epibenthic Sled and Gravity Corer. No core data was obtained for the Rowley Shoals, and limited core was available for Scott Reef. Cores were logged and dated using U series TIMS methods (University of Queensland, Centre for Microscopy and Microanalysis) by the dating techniques of Zhao *et al.* (2001) and Yu *et al.* (2006). Rock types were characterised using the Expanded Dunham Classification (Embry & Clovan 1971) for depositional textures, and the characterisation of main biological facies followed the scheme of Montaggioni (2005). Sediment data for the southern Kimberley Region and adjacent Canning

Bioregion are discussed, the latter included for comparative purposes. The data also applies to the contiguous Northwest Shelf (NWS).

Geological Setting

The onshore geology is dominated by the Kimberley Basin (Fig. 1) which consists of Proterozoic rocks

(Speewah, Kimberley and Bastion Groups) which consist of sandstones, siltstones and volcanics, with stromatolitic dolomites (GSWA 1990). Locally extensive sheetlike bodies (sills) of the Hart Dolerite are conspicuous, and in the southern part of the basin glacigene rocks are common. Narrow belts of deformed rocks (the King Leopold Orogen to the southwest and the Halls Creek Orogen to the southeast) demarcate the margins of the
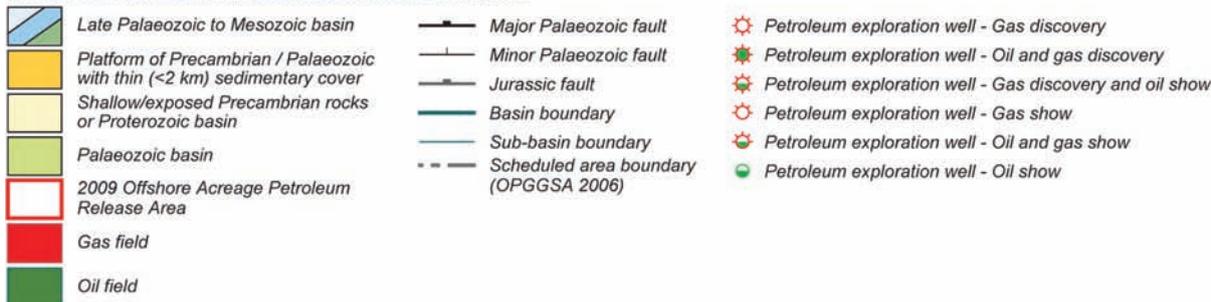

Figure 2. Significant hydrocarbon discoveries and fields of the Kimberley region. (Department of Mines and Petroleum).

Kimberley Basin (Fig. 1). These mobile belts give way to extensive onshore Phanerozoic sedimentary basins (the Canning and Ord basins, respectively). The Canning Basin is known worldwide for its exposures of Devonian reef complexes (see Playford *et al.* 2009).

Offshore the Bonaparte Basin in the northeast and the Browse Basin to the northwest contain thick sedimentary sequences which host the hydrocarbon discoveries and fields which are in various stages of development (Figs 1, 2). The geological history of the offshore regions has been controlled by breakup of the Gondwana supercontinent and earlier events spanning some 400 Ma (million years), and 3 stages of evolution are recognised: the pre-rift, syn-rift and post-rift stages (Struckmeyer *et al.* 1998; Kopsen 2002). During the pre-rift stage the region was part of an extensive basin connected to a northern seaway (Triassic-Lower Jurassic time; 250–180 Ma approx.) and marine shales to fluvio-deltaic sediments were deposited. The breakup or syn-rift events that followed increased marine influences and deposited organic-rich shales (the source rocks for most of the hydrocarbons) following which the rift was progressively infilled by shallow water sands and fluvio-deltaic sediments until rifting ceased in the Early Cretaceous time (120 Ma approx.). Thermal subsidence and reduced tectonic activity marked the subsequent post-rift stage during which mainly carbonate ramp deposits accumulated and this stage continued through to the present time, providing a package of limestones over 2000 m thick; this provided both a seal for deeper hydrocarbon reservoirs and the necessary overburden to allow maturation of the hydrocarbons. Early stages of collision of the Australian plate with the Eurasian plate to the north (Miocene time; last 28 Ma approx) caused crustal flexure and generated deep troughs and intervening structural highs (Sahul, Ashmore and Scott Platforms). These in turn provided suitable foundations for many of the offshore coral reefs of the region.

The offshore Kimberley region, particularly the Browse Basin (Fig. 2) has proven hydrocarbon reserves in the Calliance, Brecknock, Torosa (near the Scott Plateau), Ichthys and Cornea fields, with additional reserves in the Bonaparte Basin to the north, and several other discoveries undergoing evaluation and/or further exploration. Most of these will require onshore infrastructure, pipelines and marine servicing, although offshore development remains an option for the future. Also shown is the 2009 exploration acreage release area close to the Rowley Sub-basin to the south, and further exploration successes are anticipated.

The Ichthys field is now scheduled for development in the Northern Territory, a plan which may also apply for some (but perhaps not all) of the Bonaparte Basin fields.

Geomorphology and Sediments

Australia's margin in the EEZ has been recently mapped (Heap & Harris 2008) and a summary of this work for the study area (Fig. 3; Table 1) illustrates that,
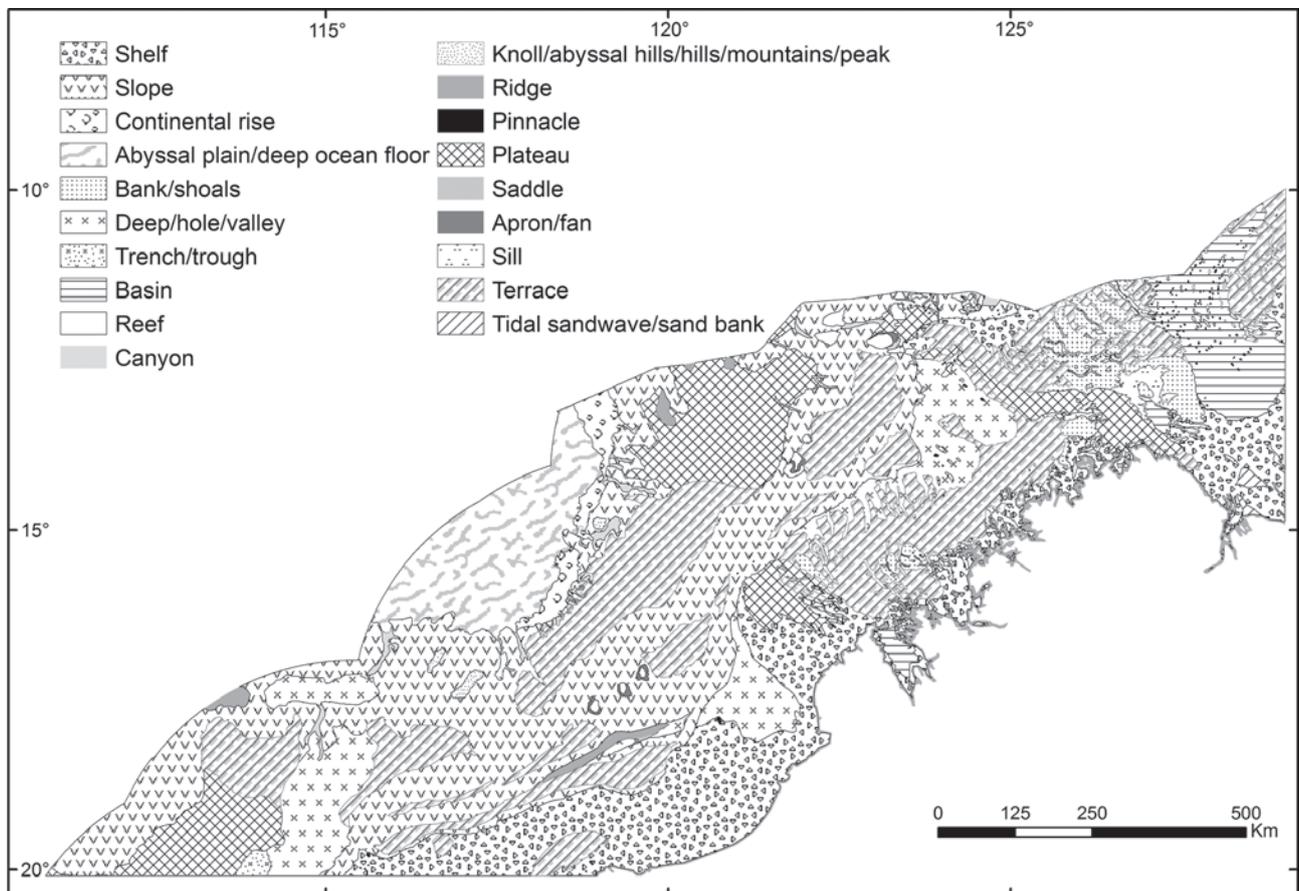

Figure 3. Geomorphology of the offshore Kimberley region, after Heap & Harris 2008.

Table 1

Summary of Geomorphic subdivisions compared with IMCRA meso-scale bioregions for the study area. Summarised from Heap and Harris (2008) and IMCRA data. The corresponding mesoscale bioregions are OSS and NWS (Oceanic Shoals, North West Shelf; shelf to slope) and KIM and BON (Kimberley and Bonaparte, coastal and nearshore shelf).

Gemorphic Provinces	Description
Shelf Zone	Adjacent to a continent (or around an island) and extending from the low water line to a depth at which there is usually a marked increase of slope towards oceanic depths.
Slope	Slope seaward from the shelf edge to the upper edge of a continental rise or the point where there is a general reduction in slope.
Rise	Gentle slope rising from the oceanic depths towards the foot of a continental slope.
Abyssal Plain/ Deep Ocean Floor	Extensive, flat, gently sloping or nearly level region at abyssal depths.
Bank	Elevation over which the depth of water is relatively shallow but normally sufficient for safe surface navigation.
Shoal	Offshore hazard to surface navigation that is composed of unconsolidated material.
Reef	Rock lying at or near the sea surface that may constitute a hazard to surface navigation.
Terrace	Relatively flat horizontal or gently inclined surface, sometimes long and narrow, which is bounded by a steeper ascending slope on one side and by a steeper descending slope on the opposite side.
Plateau	Flat or nearly flat area of considerable extent, dropping off abruptly on one or more sides.

in addition to the "normal" continental margin geomorphic units of shelf, slope and rise the offshore Kimberley region has well developed plateaux (*e.g.* Scott Plateau), terraces (*e.g.* Rowley Terrace), and banks (*e.g.* Sahul rise, Sahul bank) which interrupt the otherwise gentle seaward slopes present. These features also provide foundations for the offshore reefs, including the Sahul shoals, Ashmore, Seringapatam, and Scott Reef and the Rowley Shoals. Many of these reefs are likely to be long-established features which initially grew along a now-drowned former Miocene shoreline (Collins 2010).

Following pioneering work on the sediments of the region by Jones (1973) a detailed sedimentological survey was completed by James *et al.* (2004) for the southern part of the Kimberley region and North West Shelf (NWS), and much of the information is broadly applicable to the Kimberley so is summarised here (from James *et al.* 2004). The continental margin is a relatively simple seaward incline or ramp which can be partitioned on the basis of hydrodynamics and bathymetry into inner ramp (<50 mwd (mean water depth) -fair-weather wave base), mid-ramp (50–120 mwd-storm wave base) and outer ramp (>120 mwd). An important feature is a terrace, the base of which is at 125 mwd, occurring along the length of the shelf and backed by a 30 m high escarpment; interpreted to be the Marine Isotope Stage 3 lowstand shoreline which formed about 20,000 years BP (before present) (James *et al.* 2004).

Modern Sedimentation: Ramp Surficial Sediment

Overall the surface sediments are sand and coarser dominated (Fig. 4), ≈ 90% carbonate, and contain abundant relict material with authigenic phosphate and glauconite components. Deep-water sediments are planktic muddy sands while the shelf materials are skeletal, peloidal and oolitic. The coarse fraction (> 2 mm) is entirely skeletal, consisting of molluscs, benthic foraminifera, bryozoans, echinoids, calcareous algae and corals. *Amphistegina* and miliolids are the dominant benthic foraminifera, while most of the molluscs are bivalves. The mud-sized fraction is composed of skeletal debris, silicate clays, quartz and micrometre-sized aragonite needles. Terrigenous and high-magnesium calcite (HMC) components are highest near the shoreline, whereas aragonite needles are most abundant on the outer ramp, > 100 mwd. Outer-ramp sediment is also rich in planktics, with a rippled sediment zone between 80 and 120 mwd. A limestone pavement was encountered locally to 282 mwd. The limestone is generally poorly cemented skeletal material and ooids/ peloids in micrite matrix/ cement.

When viewed at the largest scale, aside from the strandline itself, the major break on the seafloor is an escarpment, the base of which lies at 125 mwd. In shallower waters, the sediments are mostly mud free, typically swept into sub-aqueous dunes or textured by ripples.

Integration of information from Jones (1973) and James *et al.* (2004) permits separation based largely on sediment composition, of eight sedimentary facies (Fig. 4). Particles in these facies are biofragmental, oolitic and peloidal grains, carbonate tubes and terrigenous clastics. These grains are not coeval, but a mixture of relict, stranded and Holocene elements. There are two types of relict grains: (1) skeletal intraclasts – typically fragmented to usually well-rounded altered and infilled skeletons; and (2) lithic intraclasts – angular to locally rounded clasts of cemented grainstone, packstone or wackestone of metastable carbonate mineralogy. These particles are a ubiquitous component of Australian continental shelf sediments south of North-west Cape and across the cool-water carbonate province of the southern margin (Collins 1988; James *et al.*1992, 1997, 1999, 2001). They are interpreted as having formed during former highstands, specifically Late Pleistocene MIS 3 and 4 highstands (Fig. 5), when sea level was ≈ 50 m lower than today and the shelf was intermittently submerged (James *et al.* 1997). In contrast, stranded
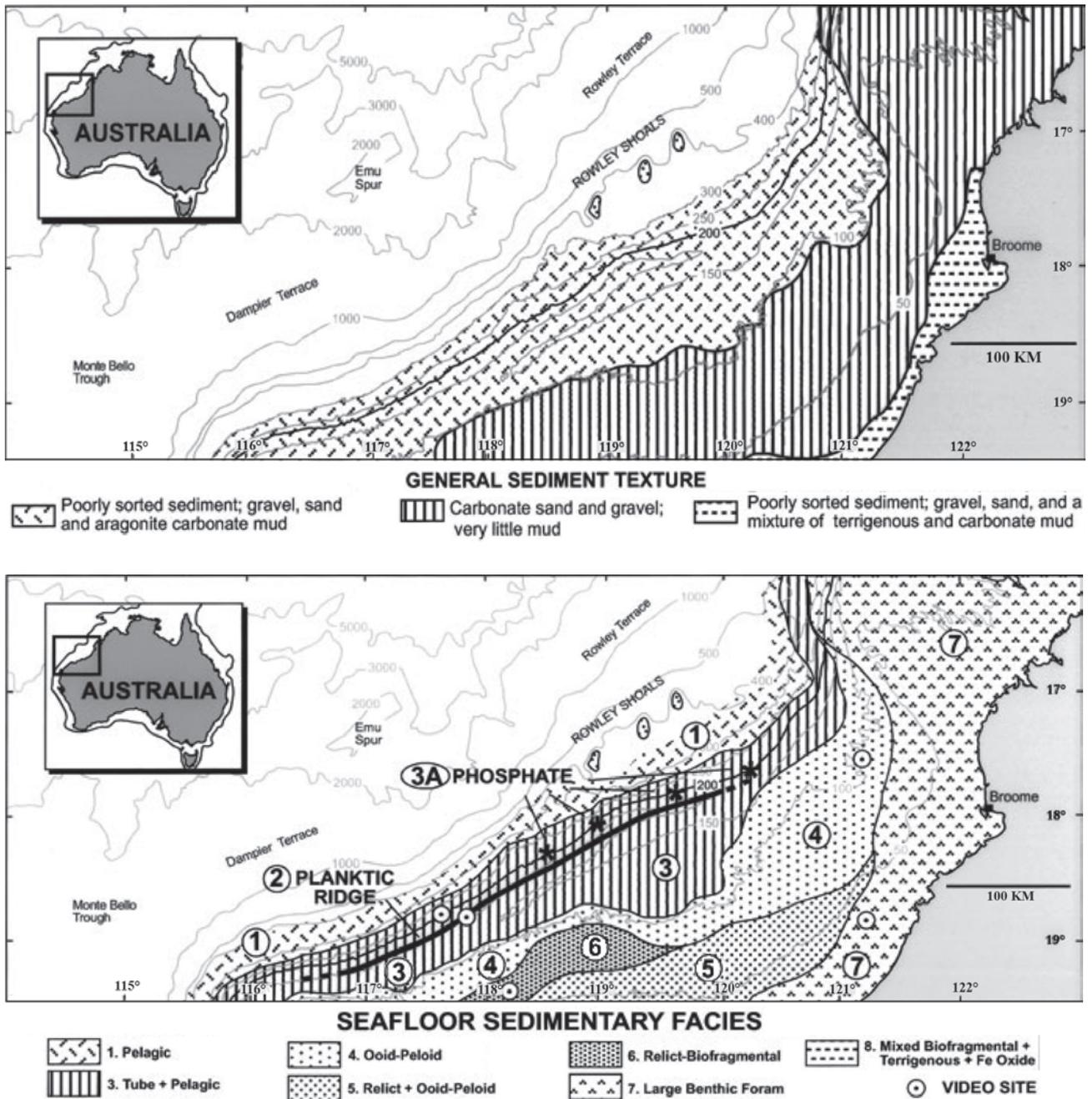
Figure 4. A. General sediment texture, and B. Seafloor sedimentary facies of the North West Shelf, modified after James *et al.* 2004.

grains are generally lightly stained, mildly abraded, younger than relict particles, but clearly out of equilibrium with their modern environment (James *et al.* 1997, 2001). The most obvious of these grains are coralline algae and ooids in water depths > 40 m. Such particles are interpreted as having formed in shallow water and having been stranded by rapidly rising sea level during the latest Pleistocene and Holocene.

The following facies are present on the outer ramp (see Fig. 4): –

Facies 1 – Pelagic sand and mud, Facies 2 – Pelagic ridge sand, Facies 3 – Calcareous tube gravel–pelagic mud, Facies 3A – Phosphate subfacies. The mid-ramp is

dominated by Facies 4 – Ooid/peloid sand, Facies 5 – Relict intraclast, ooid/peloid sand and Facies 6 – Relict intraclast, biofragment sand and gravel. The two main inner-ramp facies are: Facies 7 – Benthic foraminifera sand and gravel, Facies 8 – Mixed biofragmental–terrigenous– iron oxide sand (Facies 8: NWS region only). These facies continue as contour – following belts southward onto the adjacent NWS.

*Origin of Particles-Relict Sediment: R*elict grains are important parts of the sediment on the mid-ramp in water depths of < 150 m and most abundant (> 50% of sediment) between 80 and 40 mwd. The brown to orange to yellow-stained particles are clearly distinguishable

under the petrographic microscope using a combination of transmitted and reflected light. The brownish material is a complex mixture of clay minerals, iron oxides, aragonite and Mg--calcite manifest as either microcrystalline sediment or alteration of carbonate particles.

Stranded sediment: The most obvious of these grains on the NWS are ooids and, by implication, peloids. Some biofragments may also be stranded, but there is no clear way of telling which ones have such an origin.

Ooids are particles which range from fresh and white to locally beige in colour. Those that are white are typically polished. They are spread across the shelf from 30 to 300 mwd (Fig. 4) but focused between 60 and 150 mwd (peloids 60–150 mwd; ooids 60–135 mwd).

Ooids are generally fine to locally medium sand size, 0.25–0.75 mm in diameter, occasionally with a well-developed cortex, but most commonly with only superficial coating on a peloid core. The nucleus is also locally quartz grains inboard or benthic foraminifera, echinoid grains or bryozoans outboard. Scanning electron microscopy shows that the cortex comprises layers of tangentially and randomly oriented aragonite needles. Radiocarbon dating indicates that the ooids formed over a narrow time frame, 15.4–12.7 ka. Incremental dating of the cortex of three ooid populations points to growth occurring over ≈ 2000 years.

Peloids are generally < 2 mm in size, spherical to ovoid in shape, composed of microcrystalline carbonate and of two types (Jones 1973). SEM analysis of these peloids, some of which are ooid cores, indicates that they
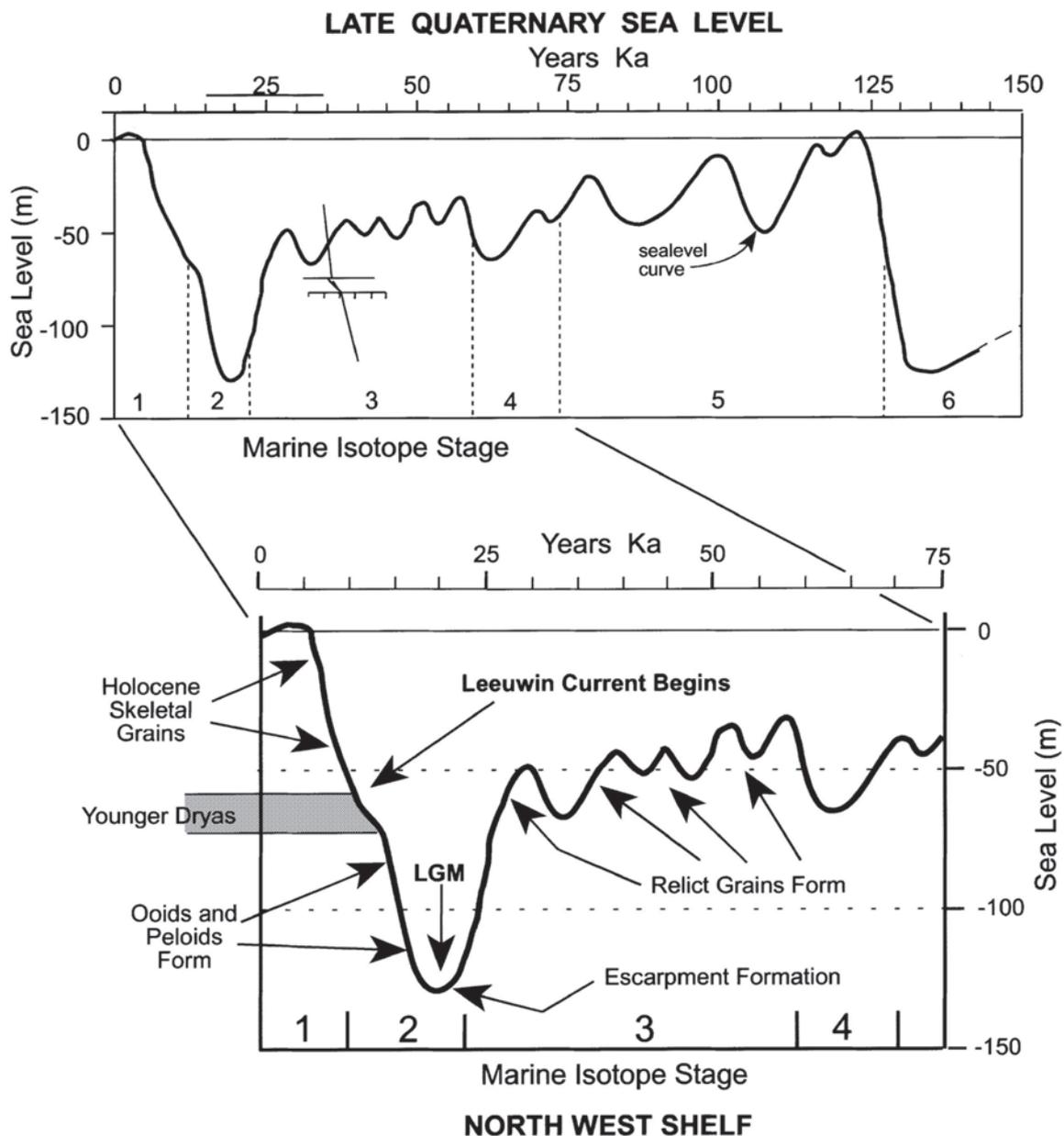

Figure 5: Late Quaternary sea level and expanded portion over the last 75,000 years showing significant events and periods of particle formation on the North West Shelf (after James *et al.* 2004).

are composed of aragonite needles, like those forming the ooid cortices. A few are also micritised skeletal grains. Some peloids are stained and so are relict, unlike the ooids. The close association between ooids and peloids implies a common environment of formation and geological age. Open marine ooids with an aragonite cortex typically form in shallow, tidal-dominated settings in water depths of less than 5 m (Simone 1980). More specifically, ooids reflect formation in environments of somewhat elevated salinity, for example on the Bahama Banks and the Persian Gulf, and in extreme conditions, as at Shark Bay (Logan *et al.* 1970). The rate of ooid growth is similar to that determined from the Bahama Banks (see discussion in James *et al.* 2004).

The period 15.4–12.7 ka corresponds to the period of rapid sea-level rise during meltwater pulse 1 A (mwp 1a) associated with the first phase of post-Last Glacial Maximum (LGM) deglaciation (Jensen & Veum 1990), before Younger Dryas cooling (Fig. 5) and slowed sea-level rise. Comparison with the Barbados curve (Fairbanks, 1989) indicates that sea level would have risen from what is now ≈ 105 to ≈ 70 mwd during this time. Specifically, it would have rapidly submerged the escarpment and spread across the wide sea floor above the crest of the cliff, creating an expansive, shallow environment. Increased aridity and wind speed over continental Australia during and immediately after the LGM, with strong offshore winds in the NWS region (Prell *et al.* 1980; Williams 2001), would have increased evaporation, thus promoting ooid formation. Such an interpretation, of evaporative Bahamian/Persian Gulf-like shallows, also explains, in part, the association of ooids and peloids because, in the Bahamas platform margin, ooid facies also coincide with peloid lithification (Purdy 1963). Oxygen isotopic compositions of ooid cortex aragonite indicate lower $\delta^{18}O$ values with decreasing age, reflecting either warming or, more likely, decreased sea-water salinity. Analysis of clays in the region (Gingele *et al.* 2001a, b) suggests that the onset of Leeuwin Current flow, and attendant less saline sea water, began ≈ 12 ka. Thus, ooid and peloid formation is interpreted as having taken place in shallow evaporative shelf environments during mwp-1a, but as having been arrested by initiation of the less saline waters of the southward-flowing Leeuwin Current during mwp-1b (James *et al.* 2004).

Biofragmental particles: The association, in general terms, is foramol (foraminifera and molluscs) in character with accessory bryozoans, typical of a heterozoan assemblage (James 1997). Yet this is too simple a classification. Inshore, to depths of ≈ 30 m in the Barrow and Dampier sectors, the environment is one of coral reefs, bryozoans and macrophytes, together with large (symbiont-bearing) foraminifera. This is an unusual consortium – part photozoan and part heterozoan. There are no ooids here, and the calcareous green algae are not calcified. It is reminiscent of the Houtman Abrolhos reefs far to the south (Collins *et al.* 1997; James *et al.* 1999). Offshore, in waters > 40 mwd, the sediment is a heterozoan assemblage with large benthic foraminifera decreasing seaward, a subtropical sediment (James 1997).

Tube facies and phosphatisation: The calcareous tubes (Facies 3) appear to post-date the sediments in which they lie. Foraminifera in the tube wall sediment are latest Quaternary in age. Radiocarbon dating of bulk sediment from the tube walls yields ages of 9.9 and 25.1 ka. Given that the sediment probably contains material of different ages, these results indicate that tubes are < 9.9 ka old, but the exact age is uncertain.

The sediment in which the tubes are developed has several very shallow-water proxies, particularly the bivalve *Anadara*, the grass meadow bivalve *Pinna* and zooxanthellate corals, all pointing to an inner-ramp environment. This environment, now in water depths > 120 m, most probably formed during the LGM lowstand (MIS 2) about 20 ka (Fig. 5).

$^{87}Sr/^{86}Sr$ values for seven teeth and bones in the same sediment average 0.709174 (range 0.709143–0.709294), indicating that they are Late Pleistocene to Holocene in age (cf. Farrell *et al.* 1995). This age is in accordance with the relatively young age of the tubes upon which phosphate has precipitated. These ages of the tubes imply that arrested sedimentation, iron and phosphate precipitation and accumulation are ongoing today. Thus, this outer-ramp region is an area of weak upwelling and/or phosphatization resulting from Fe-redox cycling within the sediments (cf. Heggie *et al.* 1990).

Planktic sediment ridge: This elongate feature, first documented by Jones (1973), is of interest because of its persistence through time. Sea-floor samples are always pelagic sediment, particularly pteropods, with a fine-grained benthic component. Surface ripples indicate that sediment movement is to the south. Radiocarbon dating of pteropods and planktic foraminifera from two localities yields ages of 0.35 and 9.2 ka (thousand years), confirming the contemporary age of the material.

The structure is interpreted here as a high surface productivity phenomenon. The most likely explanation is that it corresponds to a zone of near-surface shear between the Leeuwin Current and Indian Ocean Water, thus promoting upwelling and nutrient enhancement.

Kimberley and North West Shelf Surface Sediment and Processes

The sediments are palimpsest, with diverse particle types of different ages, variably mixed by biological and hydrodynamic processes to form a complex facies mosaic, some of which contains many particles that are out of equilibrium with the present sea-floor setting. A summary of ramp sedimentation is shown in Figure 6 (after James *et al.* 2004).

Implications for the Understanding of Ramp Sedimentation

The Kimberley and NWS is a carbonate ramp on the scale of such carbonate realms as the great Bahama Bank and southern Persian Gulf. Almost all attributes are determined by regional oceanography, in sometimes unexpected ways. Inner-ramp facies on the NWS are a complicated mix of photozoan and heterozoan elements, reflecting an oligotrophic oceanic setting repetitively perturbed by the influx of fine sediment and nutrients from land. The high energy of the marine system sequesters these terrigenous clastics adjacent to the shoreline, and they are not transported offshore.

Saline water outflow along the sea floor, the result of evaporation on the inner ramp, appears to have subdued
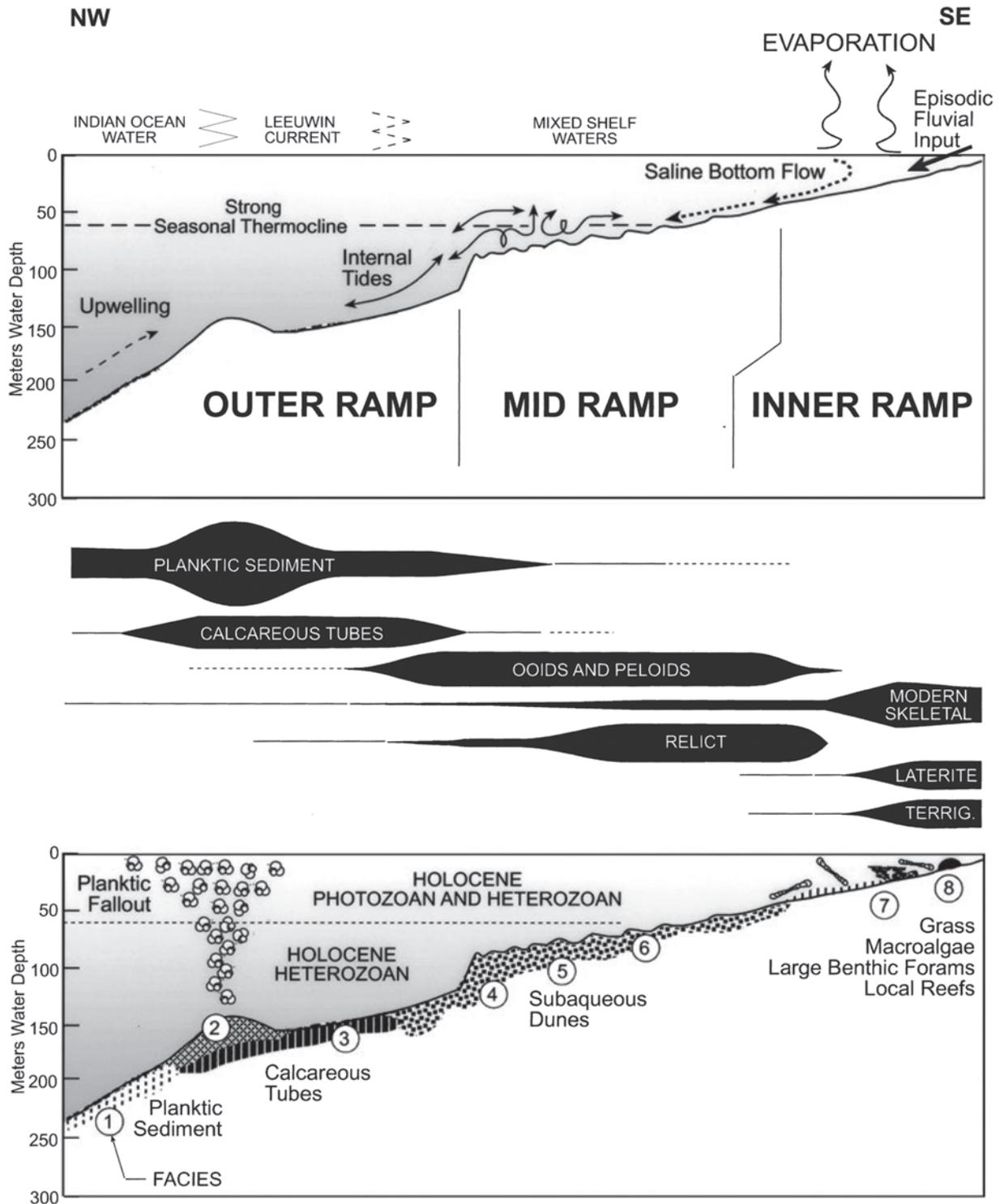
Figure 6. Summary diagrams illustrating (top) the major oceanographic-climatic factors affecting shelf sedimentation, (middle) the spatial distribution of major particle types across the ramp and (bottom) major ramp features and sedimentary facies (see also the facies map in Fig. 4). After James *et al*. 2004, Figure 11.

or arrested modern benthic carbonate production on much of the mid-ramp. This may be, in part, why the mid-ramp is not more distally steepened.

Changing late Quaternary oceanography has had a profound effect on NWS carbonate sedimentation. During the last global sea-level low-stand and early parts of the subsequent transgression, the NWS was a site of warm-water carbonate sedimentation, with strong offshore winds probably enhancing upwelling and eva-poration. There is clear evidence that, during the initial stages of sea-level rise, ooids and peloids, a classic warm-water facies, developed across many tens of kilometres of the then shallow shelf. Yet, this sedimentation ceased ≈ 12 ka, when the lower salinity

Leeuwin Current began to flow strongly. It is this change in oceanography that probably resulted in a shift to the present dominance of skeletal carbonate production. In this situation, carbonate production has not been able to keep pace with rising sea level, implying an overall reduced sedimentation rate that has left the seafloor veneered with a mixture of old and new deposits, many of which are out of equilibrium with modern environments.

As the region illustrates: (1) the rapid rate of sea-level rise stranded shallow-water sediments; (2) the changing oceanography altered the character of the carbonate factory from photozoan to heterozoan (and mixed heterozoan/photozoan on the inner ramp); and (3) the high-energy (waves, swells, cyclones, internal tides) mixed sediments formed at different times during transgression. This situation is most obvious on the NWS because the area is near the temperate–tropical carbonate system boundary, and so dissimilar carbonate sediments from different systems are mixed. This large oceanic ramp, located in the tropics, yet near the temperate carbonate realm, is one of the largest such systems in the modern world. The surficial carbonate sedimentary facies display complexities that are largely explainable in the context of modern and late Quaternary oceanography.

Reefs and Banks of the Oceanic Shoals Biozone

Coral reefs are widespread along the Kimberley coast and comprise a major geomorphic feature along the continental shelf edge from 12°S to 18°S (Fig. 7). Fringing reefs intermittently occur along an extensive portion of the coastal region. These reefs are very poorly known and endure in a remarkably inhospitable environment with high sediment input and high hydrodynamic energy, but they have been suggested to be of international significance and are in need of intensive study (Chin *et al.* 2008).

Whilst the understanding of the fringing reefs of the Kimberley still remains a gap in our knowledge, described here are aspects of the morphology, internal architecture and Quaternary growth history of some of the offshore reefs within the Oceanic Shoals Biozone (Fig. 3; Table 1) which borders the continental shelf of the Kimberley region, based on published reports, seismic and limited core data, providing the first account of Quaternary reef architecture for some of the northernmost coral reef systems of Western Australia. These reefs (except Scott Reef; Collins *et al.*, this volume) remain relatively poorly known geologically since the pioneering studies of Fairbridge (1950), unlike the well studied Great Barrier Reef, on Australia's northeast coast (Hopley *et al.* 2007).

Reefs and shoals of the Sahul Shelf

Marginal to the Sahul Shelf (north Kimberley) and close to Timor are a series of isolated submerged shoals (Echo Shoals, Big Bank and Karmt Shoals) (Fig. 7; Heyward *et al.* 1997). The shoals formed a string of banks seaward of the palaeo-coastline, some with vertical relief of over 300 m, and were drowned in the last 20,000 years (Lavering 1993), terminating the major carbonate

production derived from corals. Thereafter, the carbonate accumulation that maintains many of the banks derives from the *in situ* growth of *Halimeda* and accumulation of its fragments with contribution from a diverse reef biota of lesser abundance (Heyward *et al.* 1997). The interaction of subsidence and sea level rise has presumably drowned coral reef growth, and without the constraints imposed by the photic limits applicable to corals *Halimeda* has become the major constituent of reef/bank growth in this region.

Ashmore Reef

Ashmore Reef is an ovoid platform reef at 12°20'S on the edge of the shelf at the Browse/Bonaparte basin boundary (Fig. 7). Built on antecedent topography, the reef is the largest emergent reef and has the highest biodiversity of any reef on Australia's western margin (Glenn & Collins 2005). There are three vegetated cays, two lagoons separated by a calcareous rise, numerous patch reefs, intertidal flats, seagrass beds, lineated and non-lineated reef flats, algal pavement, and a precipitous reef front with spur and groove. The reef growth model has 3 phases (Glenn & Collins 2005): 7.5-6-5 ka: subtidal reef growth over antecedent topography during rapid sea level rise; 6-5-4-5 ka: transitional growth, catching up to slowly rising sea level; 4-5 ka-present: lateral extension phase, with broad reef flats developing as the reef front/crest reached sea level. Holocene reef thickness is about 20 metres.

Seringapatam Reef

An annular reef 8 km long and 9.4 km wide encloses a lagoon 20 m deep, with a narrow northeast passage connecting it to the ocean (Berry & Marsh 1986). The western reef is broader than that on the east (1500 m vs. 1200 m). There is a well developed reef crest boulder zone, a coralline algal rim, spur and groove zone, with coralline algal-covered grooves, then living coral to about 30 m (Berry & Marsh 1987). There are no seismic or other subsurface data available for this reef.

Scott Reef

One of the most significant offshore reefs is Scott Reef at 14°S (Figs 7, 8). This reef and the associated small carbonate platform grew along an old Miocene continental margin, and the reef has maintained its development despite rapid subsidence of the shelf edge since the mid-Miocene. The modern reef is subject to cyclones and bleaching (Smith *et al.* 2008; Heyward *et al.* 1997) and its remote location and distance from the coast (up to 400 km) positions the reef amongst the most pristine coral reef environments remaining in the world (Chin *et al*. 2008).

Scott Reef rises from depths of 400–800 m on the distal portion of a carbonate ramp, and is similar in setting to 'downslope buildups' (*sensu* Read 1985). It is a complex of two large isolated coral reefs separated by a deep channel; the pear-shaped North Reef and the crescent-shaped South Reef (Berry & Marsh 1986; Fig. 8). North Scott Reef is continuous except for two narrow passages, one in the southwest, and one in the northeast, with similar reef flat dimensions throughout. The outer reef flat is a mixture of scattered large boulders and
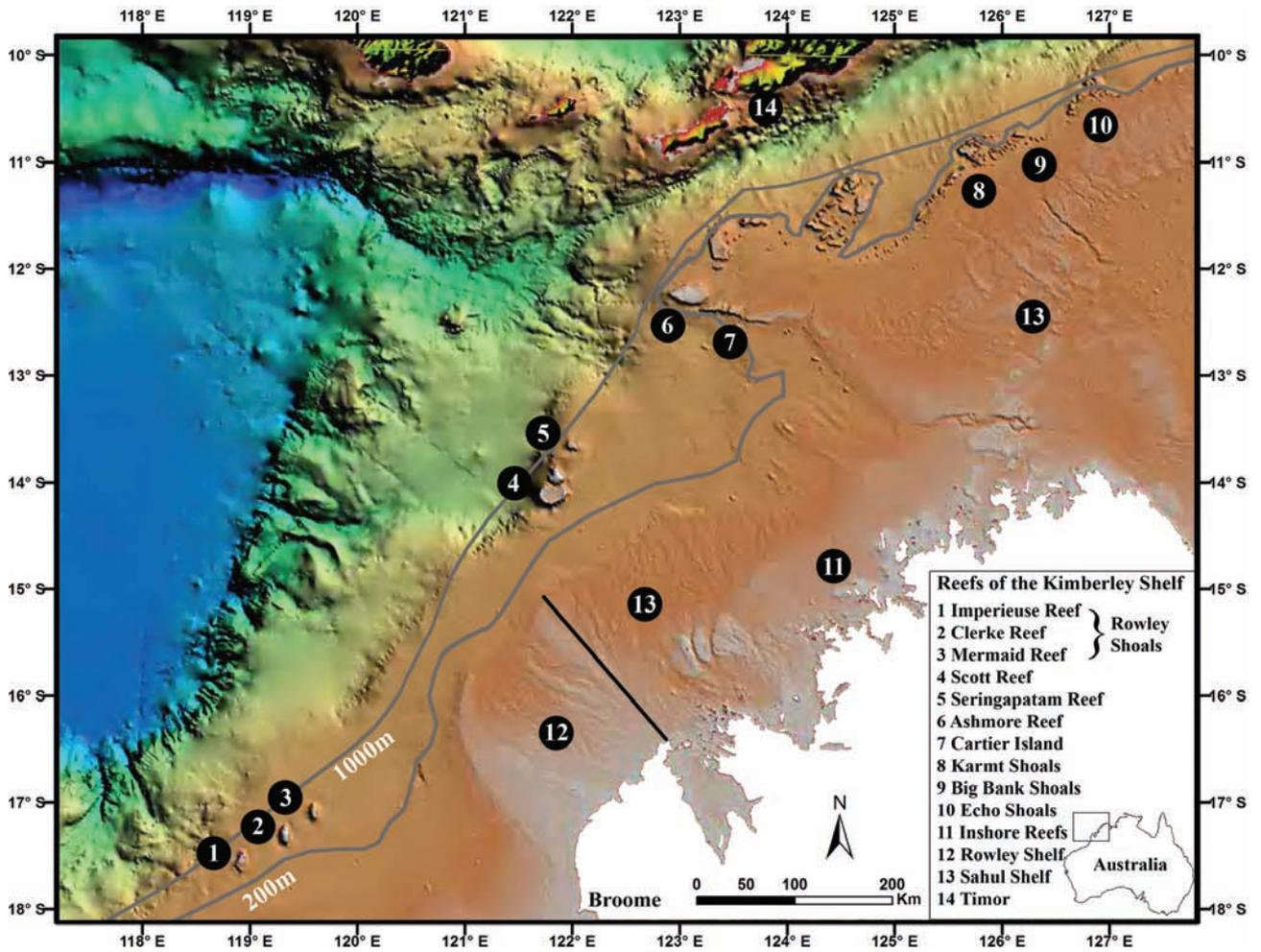
Figure 7. Location map of the Kimberley region, showing reefs mentioned in the text. Data for topography provided by Geoscience Australia.
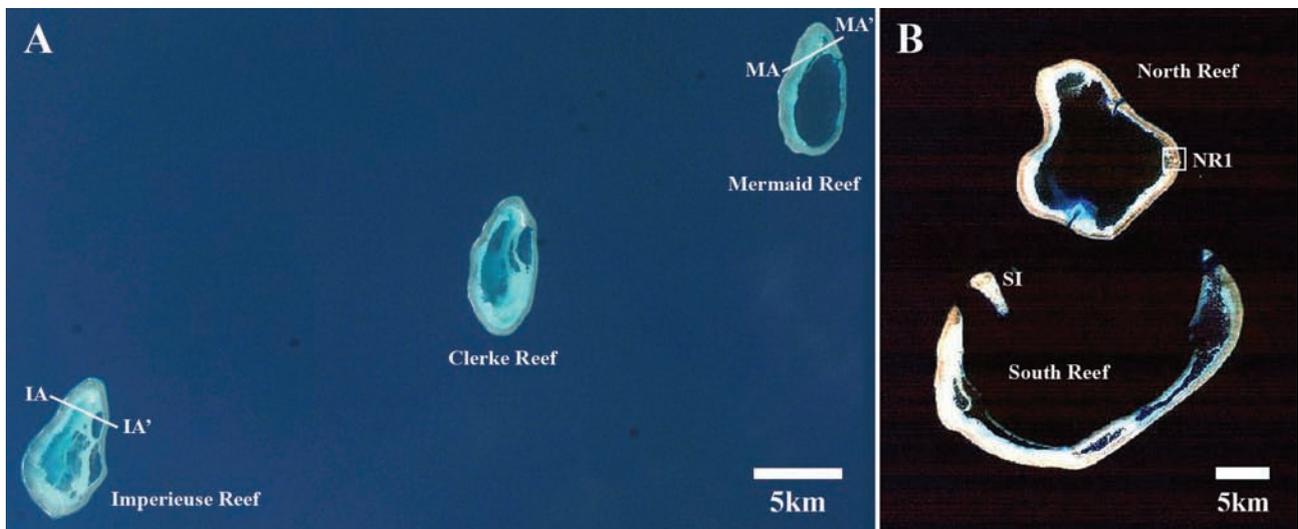

Figure 8. Landsat images of Scott Reef and Rowley Shoals. Location of borehole NR1 is shown in North Scott Reef.
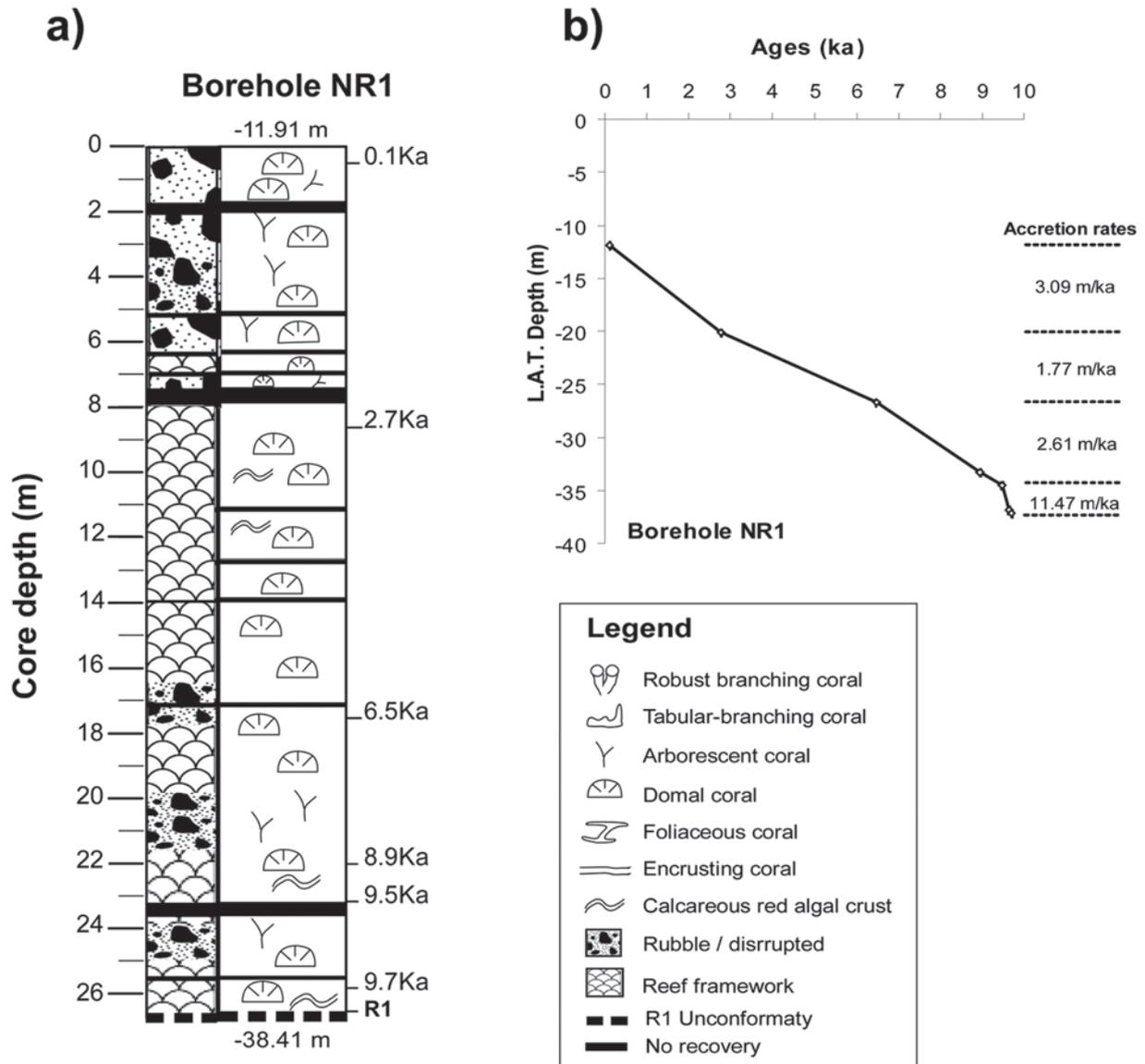
Figure 9. Summary of U-series dates for Holocene core NR1, North Scott Reef. A) Holocene chronology, reef community and lithology; b) Growth history curve for forereef core site NR1, North Scott Reef. For core location see Figure 8.

occasional living corals. The outer reef gives way on its seaward margin to a gentle slope followed by an irregular outer slope with surge channels extending to 30 m and steep gradient to seaward. The inner reef has low coral cover, some algal turf, and lacks a distinct boulder zone. The back reef is deeper, with a more diverse coral fauna, and the lagoon is sandy with scattered corals (Done *et al*. 1994).

South Reef is open to the north, and is 27 km wide (east-west) and 20 km from north to south. The distance between the reefs is 5 km and the intervening channel is 400–700 m deep. The reef flat of the western part of South Scott Reef is over 2 km wide, and 600 m of reef flat is emergent at low water. Sandy Islet is a small, unvegetated sand cay situated atop a detached northwesterly portion of the reef. The eastern part of the reef is similar in morphology to the west reef, also with a detached sand cay, which is the only portion emergent at low water. The outer reef generally has encrusting

coralline red algae and minor corals, and the reef flat includes boulder rubble, sand flats, algal turf and minor amounts of coral. The back reef is sandy with scattered large *Porites* colonies, other corals and sparse seagrass. Lagoon depths inside South Scott Reef are 35–55 m (ca. 30 m in North Reef) and there are isolated coral knolls, sandy areas, and hard substrates with sponges and stunted coral communities (Done *et al*. 1994).

The Holocene reef section is composed of porous but relatively unaltered reef framework with lesser amounts of carbonate sediment; some intervals, particularly those of branching corals, are rubbly, partly as a result of accumulation of both framework and infill material (Fig. 9). The dominant frame builders in borehole NR1 (fore-reef of North Reef) are communities of two types: arborescent (branching) acroporides, and domal (massive) corals mainly poritides; these exist as end member communities as well as in mixed associations. Reef initiation and early stages are characterised by

coralline red algal crusts and domal coral, with gradual increasing contribution of branching corals. The Mid to Late Holocene is dominated by domal corals, and this facies is replaced by arborescent and domal facies during the Late Holocene to present.

Uranium-series chronological data obtained for NR1 is in agreement with stratigraphic data and the expected position of the pre-Holocene unconformity (R1), corresponding to Marine Isotope Stage 1 (MIS1), at about 26.5 m core depth (-38.41 m relative to Lowest Astronomical Tide; LAT) (Fig. 9). The earliest dated settlement of reef building coral community recorded for the borehole is 9.7 ka at 25.75 m core depth (-37.16 m LAT depth), followed by subsequent development during the Holocene.

The average accretion rate for the Holocene section of borehole NR1 is calculated as 2.64 m/ka. However, the accretion rate curve suggests four distinct phases of reef development (Fig. 5b; Table 1): an initial and faster development from reef initiation to 9.47 ka, characterised by an accretion rate of 11.47 m/ka; accretion rate gradually reduces to a minimum of 1.77m/ka during middle Holocene (6.4–2.7 ka), returning to increase to 3.09 m/ka from late Holocene to present (Fig. 5b).

Variations in the accretion rates during the Holocene can be explained by the dominant coral communities during the middle Holocene (Fig. 9a, b), which is characterised by slow growing domal corals, such as the genus *Porites*. In contrast, higher accretion rates were recorded when there are greater proportions of arborescent forms (see also Blanchon & Blakeway 2003; Montaggioni 2005). Whilst the faster accretion rates recorded during reef initiation were expected, the more consistent slow rates for most of the Holocene are more representative of the overall Holocene reef development such as commonly found in Indo-Pacific reef margins (Montaggioni 2005), resulting in the generation of a 25 m thick Holocene section at Scott Reef. For a fuller discussion of Scott Reef see Collins *et al.*, this volume).

Rowley Shoals

The Rowley Shoals (Figs 8, 10) comprise a group of three offshore isolated reefs, the Mermaid (17°06'S – 119°37'E), Clerke (17°19'S – 119°21'E) and Imperieuse (17°35'S 118°55'E – 17.583°S) reefs. Described as the most perfect morphological examples of shelf atolls in Australian waters (Fairbridge 1950), the three shoals have similar dimensions, shape, orientation and distance apart, and all rise from the distal ramp of the North West Shelf. From northeast to southwest the reefs rise from progressively shallower depths on their landward sides; Mermaid Reef from 440 m, Clerke Reef from 390 m, and Imperieuse Reef from 230 m. Each atoll (length range 15–17 km, width range 7–9 km) has north-south orientation, is pear-shaped with the narrower end to the north, and has a reef which encloses a single central lagoon which is ovoid and relatively deep in Mermaid Reef, but becomes increasingly shallow and segmented in Clerke and Imperieuse reefs. About two thirds of the way up its eastern side, each system has a narrow passage (or passages), through which tidal flushing and sediment exchange occur (Berry & Marsh 1986).

Mermaid Reef (Fig. 10) has, on its western side, an outer reef flat (0.5 km wide) which is exposed at low tide, and a back reef of similar width, backed by a 1 km wide sand flat. The eastern margin is only 0.6 km wide and the sand flat is absent. The western outer reef slope has well-developed spur and groove, the outer reef has slow-growing coralline red algae and corals, while the back reef flat has a cover of living and dead coral and algal turf (Berry & Marsh 1986). At Clerke Reef the shallow (<10 m) lagoon is segmented into three parts by sand sheet development (Collins 2002). Imperieuse Reef has a lagoon partitioned into three basins by sand sheet development but the two along the eastern edge are deeper than the larger, central basin which is extensively infilled by a meshwork of coral growth, composed of flat-topped coalescent reef with intervening sand-floored depressions (Collins 2002). The coral assemblages described for Scott Reef by Done *et al.* (1994) are also recorded at Rowley Shoals. Differences in reef morphology, hydrodynamic exposure and ponding are reflected in the assemblages.

The Rowley Shoals are similar in gross morphology (ovoid shape, with annular reef and central lagoon; similar length and width) in their down- ramp setting (but they rise from increasing depths to the northeast, 230 m at Imperieuse to 440 m at Mermaid Reef) and wind, wave and tidal regimes. They differ in morphology by an increasing degree of lagoon infill from northeast to the southwest, from the open, ovoid and 20 m deep Mermaid lagoon, through the partially infilled and partitioned Clerke lagoon, to the shallow, more fully infilled Imperieuse lagoon (Fig. 10).

It could be argued that different degrees of sediment retention or export from the lagoons through leeward channels could influence lagoon infilling, and a plume of expelled lagoon sediment was detected in nearby seafloor samples at Mermaid Reef collected at 400 m depth (Collins 2002). Similar northeasterly leeward channels at Clerke and Imperieuse Reefs are poorly developed, only a few metres wide, and transport much smaller sediment loads, so these lagoons apparently retain far more sediment than Mermaid Reef.

Seismic profiles for Mermaid and Imperieuse Reefs show the pattern of reef growth in both, with the Holocene reef growing in the accommodation (space) provided by a saucer-shaped, subsided, last interglacial reef. The calculated subsidence rate since the last interglacial (Fig. 10) is 1 m/6000 y, comparable to that of Scott Reef. However, there is a striking difference in the depth of the last interglacial reflector in the lagoon, which is uniformly 37 m below sea level in Mermaid Reef, but only 18 m below sea level in Imperieuse Reef (Fig. 10). Aside from indicating differential subsidence since the last interglacial (ca. 125 ky ago; see Fig. 11), assuming the lagoon floor elevations were initially similar, these data indicate that the accommodation available for Holocene reef growth and lagoon infill at Imperieuse Reef was only 50% of that available at Mermaid Reef, and this is a key long term control on the different amounts of lagoon infill during the same time interval observed between the two reefs, and the resultant morphological series (Fig. 10).
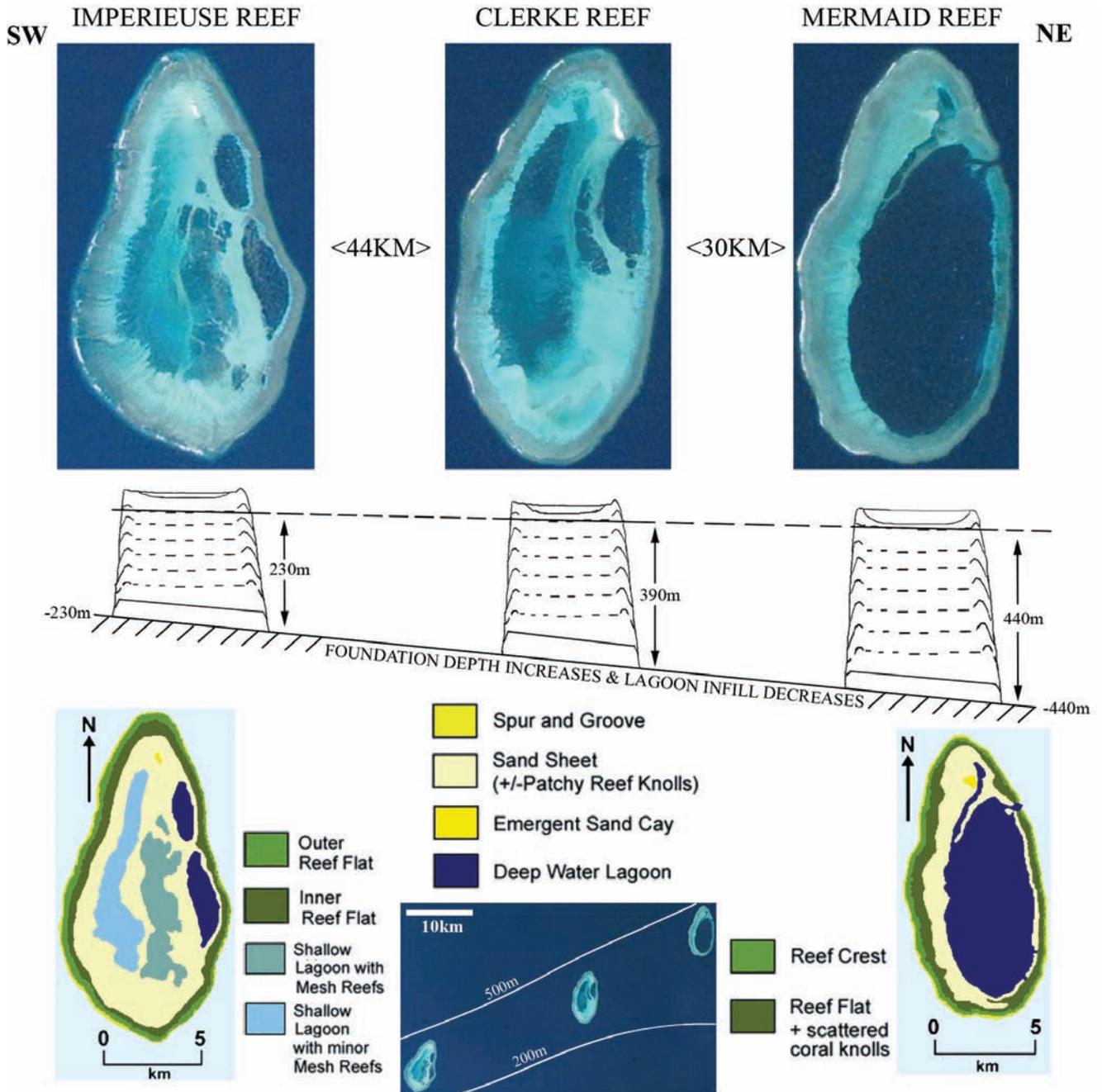
Figure 10. Landsat images, substrate maps, plan and cross section of the Rowley Shoals, the section redrawn from seismic data. The pattern of decreasing lagoon infill northward reflects differential subsidence since last interglacial time (the previous event of reef growth to the Holocene reefs; 37 m for Mermaid but only 18 m for Imperieuse Reef) so that infilling of available space is near complete in the latter, but remains incomplete in the former. Note the differing elevations of the shelf surface on which the shoals have developed, and the vertical disparity between these apparently identical platforms which (assuming similar initial ages) likely reflects a higher long term subsidence rate, and greater sustained vertical growth for Mermaid Reef. (Seismic data from Collins 2002).

Discussion

This paper has attempted to provide an earth science perspective from which to consider present and future issues for marine science and management of the unique Kimberley area. It is clear that the gathering pace of offshore activities will require greater attention to such considerations in the coming years. The hydrocarbon resource potential and long term exploration and production of the Browse and Bonaparte Basins is evident from existing and proposed field developments in a global climate of declining reserves and increasing demand for gas in our region. Much of this activity lies within the deep waters near the continental margin in the Offshore Shoals Bioregion, but impacts on other regions may follow.

With the onset of plate collision between the Australian and Eurasian plates since Miocene time, (subsidence rate of 15–20 m/Ma, Sandiford 2007)
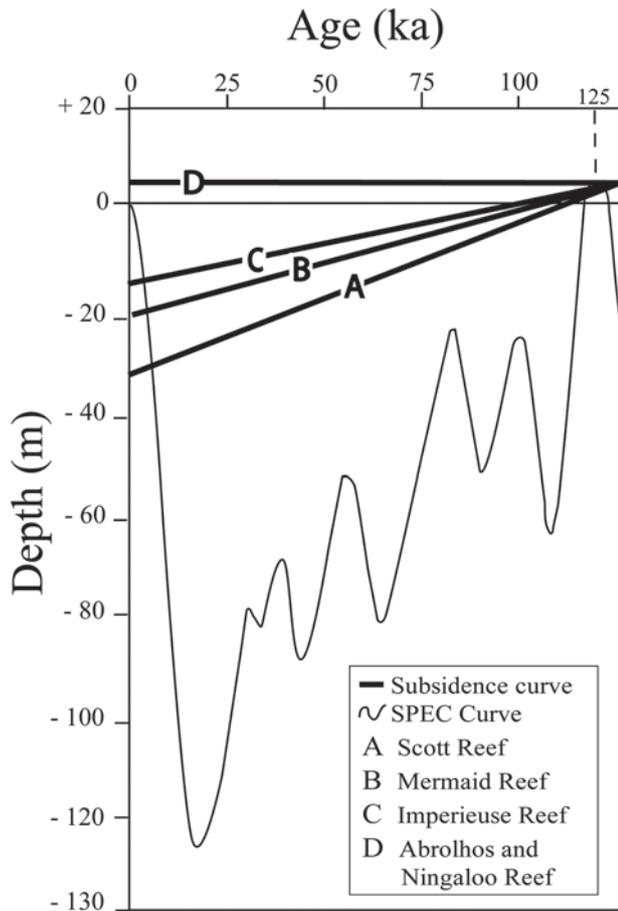
Figure 11. Global sea level curve and subsidence rates determined from seismic data for NWS reefs, based on depths of last interglacial surface. Sea level curve based on Chappell & Shackleton (1986).

reef systems and generate high coral buildups despite their position bordering a subsiding ramp margin. In the case of the three Rowley Shoals differential subsidence can be linked to a transitional series of lagoon infill and geomorphology in these otherwise similar oceanic atolls.

The core described for North Reef is significant because it serves to confirm previous seismic interpretations, but has additional importance. Ocean-facing reef cores are uncommon from high energy settings due to the difficulty of the logistics involved in their collection, and the core data presented here is therefore an important contribution to the characterisation of the fore-reef zone of shelf edge reefs. The Indo-Pacific reef growth phase (termed RG111) was characterised by moderate rates of sea level rise of 10mm/year from 11 to about 7–6.5 ka BP until sea level stabilization at or 2m above its present position (Pirazzoli 1996, Collins *et al*. 2006). Pre-Holocene accommodation was created at a calculated subsidence rate of 0.25m/ka (Collins 2002), and subsidence was an important control of overall reef morphology.

Coral reefs worldwide are under increasing threat from anthropogenically induced climate change including temperature-induced coral bleaching (Hoegh-Guldberg 1999; Wilkinson 2008) which is often exacerbated by human activities. The remoteness of the Kimberley region provides little protection from the former but is likely to continue to limit the latter impacts, however these may increase in future. Further biological and geological research is needed in this region to examine reef response to past climate and sea level change and to provide analogue information for future climate change management.

structural remnants such as the Scott Plateau, Rowley Terrace and Sahul Rise have provided suitable substrate for coral and *Halimeda* build-ups offshore, and despite the sea level oscillations of the Pleistocene and the long term subsidence of the continental margin these reefal buildups have persisted as long lived structures which have vertical growth of as much as 400 metres.

Overall the surface sediments of the NWS are sand and coarser dominated carbonate, and contain abundant relict material with authigenic phosphate and glauconite components, the latter reflecting upwelling. Deep-water sediments are planktic muddy sands while the shelf materials are skeletal, peloidal and oolitic. The coarse fraction (> 2 mm) is entirely skeletal, consisting of molluscs, benthic foraminifera, bryozoans, echinoids, calcareous algae, corals, benthic foraminifera, and bivalves. They are mixtures of relict, stranded and bioclastic sediment, and reflect both changing sea levels and oceanography interacting with biodiversity. The onset of the Leeuwin Current some 12 ka ago terminated deposition of precipitated particles (ooids, peloids) and favoured bioclastic production.

Unlike the drowned reefs, now *Halimeda* shoals of the Sahul Shelf further northward, all of the Kimberley coral reefs described here have been able to survive as resilient

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