6. Summary and Discussion

Textural and compositional data generated during this study for the NWMR and NNMR permits a quantitative comparison of sedimentology for Australia's Northwest and Northern Margin. The data builds on previous predominantly qualitative studies that currently exist for the region. Previous work for the area has focussed principally on the shelf, and consequently the following discussion is largely restricted to a comparison of our findings with the results of previous sediment models for the shelf. The implications of seabed sediment distribution for marine habitat mapping are also discussed.

6.1. SEDIMENT TRENDS OF THE NWMR

New consistent quantitative data for the NWMR have revealed regional scale patterns in sediment distribution not apparent in previous studies and forms a framework within which local scale patterns can be understood in a regional context. New data reveal some of the seabed complexity. At a regional scale our data show that seabed sediments become finer with increasing water depth in a margin parallel pattern. Variation in sediment texture and composition generally decreases with increasing water depth, with sediments on the rise and abyssal plain/deep ocean floor being relatively homogeneous compared to those on the slope and shelf. The fining and homogenisation of sediment texture with distance offshore is predominantly the result of decreasing energy levels and sediment transport mechanisms (for a detailed explanation see Section 3).

The shelf is predominantly composed of sand, and the abyssal plain/deep ocean floor is composed of mud. Areas of gravel occur mostly on the inner, middle and outer shelf/slope and are generally absent from the abyssal plain/deep ocean floor. This broad zoning and fining of sediment type with water depth has also been observed in similar reports by Geoscience Australia, notably on the South-West Australian margin (Potter et al, 2006). Calcium carbonate concentrations are highest on the inner, middle and outer shelf, and represent either relict or recent carbonate deposits. The high concentration of carbonate within this region has also been observed by Carrigy and Fairbridge (1954), Colwell and von Stakelberg (1981), Dix (1989), Dix et al. (2005), James et al. (2004), Jones (1970, 1973), and van Andel and Veevers (1967).

At a local scale our results agree with previous sedimentological work on the inner, middle and outer shelves and slope. Our data indicate distinct changes in sediment characteristics to the north of the Leveque Rise where high mud concentrations and low sand concentrations occur, similar to that noted in previous studies (van der Kaars, 2003; Carrigy and Fairbridge, 1954; Jones, 1971; Jones, 1973). New data have allowed us to more accurately map the extent and recognise the regional significance of this change.

High resolution data generated by Geoscience Australia for the seabed in the EEZ have indicated that geomorphic features are characterised by a combination of several environments with zones of transition between these. For some geomorphic features, the new data allow us to more accurately predict and distinguish between the range of environments present and, where data are adequate, estimate the relative proportions of these. Distinct sedimentary environments occur in some geomorphic features and these including: abyssal plain/deep ocean floor, ridges, terraces, slope, deeps/holes/valleys, and banks/shoals. Establishing relationships between substrate type and geomorphic feature will assist in creating a more accurate prediction of the sedimentary environment in regions with sparse sample coverage.

6.1.1. Inner Shelf

Seabed sediments of the inner shelf are sand dominated, with localised accumulations of gravel and a large carbonate component (40-100%). Bulk carbonate content increases with sand content and sand content decreases with water depth. Our data and indicate that localised deposits of mud and gravel occur in the vicinity of the Dampier Archipelago, Port Hedland, Broome and to the north of the Leveque Rise. To the north of the Leveque Rise, inner shelf sediments are dominated by higher proportions of mud (20-40%) and gravel (40-80%) and lower proportions of sand (20-40%) and carbonate (20-40%). This pattern corresponds to the sedimentology of the region as observed by Carrigy and Fairbridge (1954). We also detected additional comparable areas of gravel (~40-80%) present locally on the inner shelf of the Bonaparte Gulf. Dix (1989) and Dix et al. (2005) observed that seabed sediments on the inner Dirk Hartog Shelf are dominated by carbonate. Our results agree with this and show that this trend also extends across the Rolwey Shelf to the Leveque Rise.

Associations between our sediment data and previous facies models for some areas of the inner shelf are difficult to resolve due to local areas of sparse data. James et al. (1999) observed low amounts of terrigenous sediment on the inner shelf, with an increase in material proximal to river discharge sites (e.g. sediments of the Dirk Hartog Shelf that reflect discharge from the Gascoyne River). Although elevated terrigenous content of sediments may be significant at the scale of these studies and should be noted for planning purposes, our data indicate they are confined to relatively small areas located near the coast and do not significantly affect the sedimentology of the shelf when assessed at a regional scale.

6.1.2. Middle Shelf

At a regional scale, sediments of the middle shelf mostly comprise carbonate sand. Carbonate content increases with sand content. Gravel content is generally low, however large aggregations occur within the Bonaparte Gulf. Jones (1970, 1974) noted that seabed sediments of the middle shelf are coarse and sand dominated, with ~90% carbonate composition. Our results agree with his study and show that the trend extends further south to the extent of the Dirk Hartog Shelf.

At a regional scale the greatest variety of sediments occur in areas containing several geomorphic features (i.e., basins within banks, pinnacles within basins). This is particularly evident where features with a distinct sedimentology are interspersed with other features with a distinct sedimentology (i.e., gravel dominated pinnacles located within the homogenous, sand dominated unassigned shelf).

Our data confirm the aggregation of carbonate on the middle Rowley Shelf. This carbonate deposit contains 80-100% bulk calcium carbonate and is inferred from previous literature as a relict carbonate deposit from the Late Quaternary (James, 2004).

New data for the North West Shelf Transition (NWST) indicates that the area of the middle shelf included in this bioregion has a unique sedimentology compared to the rest of the Northwest margin. For the majority of the NWMR, the middle shelf zone is dominated by carbonate sand. The NWST however is characterised by a high proportion of mud and lower proportion of carbonate. Our data provide further evidence in support of the facies model of Carrigy and Fairbridge (1954), who described this region as showing a distinct change in seabed sediments north of the Leveque Rise. A possible explanation for the distinct change in seabed sediments in the region may be the result of high levels of river discharge and subsequent terrigenous sediment into the Bonaparte Gulf.

6.1.3. Outer Shelf and Slope

Our data indicate that at a regional scale, seabed sediments of the outer shelf and slope are dominated by carbonate sands. Further, mud content increases with water depth on the mid to lower slope. Offshore the shelf break in the NWMR, pre-existing sediment data and facies models are relatively scarce, and our data have characterised much of this environment for the first time. Addition of data in geomorphic features occurring on the outer shelf and slope has facilitated the first quantitative analysis of the sedimentology of features occurring at these water depths in the NWMR, including trenches, reefs and large plateaus and terraces. Sediment data show that some features in this zone are characterised by a distinct sedimentology that differentiates each feature and also forms occurrences of the same feature elsewhere in the NWMR. These features include terraces, ridges and slope.

Our data provides further evidence for extensive carbonate sand deposits at the shelf edge (Carrigy and Fairbridge, 1954). The slope contains a higher proportion of mud (40-80%) than found on the shelf. The Exmouth Plateau is a significant geomorphic feature of the outer shelf and slope and contains 20-60% sand and 40-80% carbonate, also noted in Colwell and von Stackelberg's (1981) facies model.

6.1.4. Abyssal Plain/Deep Ocean Floor

Sediment samples procured for this task from the abyssal plain/deep ocean floor have significantly increased the sample coverage and understanding of the sediment properties. The abyssal plain/deep ocean floor is a relatively homogenous sedimentary environment dominated by siliclastic mud with small inclusions of sand and no gravel. Particle size and bulk carbonate content decreases with increasing water depth, as observed by Colwell and von Stackelberg (1981) and Veevers et al. (1974). Our data support the findings of Colwell and von Stackelberg (1981) who described the sedimentology of the abyssal plain/deep ocean floor as siliceous clay. However, the carbonate content of sediments in deep water areas of the NWMR are now known to be more spatially variable than previously reported with carbonate content as high as 70% locally.

6.2 SEDIMENT TRENDS OF THE NOMINATED AREA OF THE NNMR

New consistent quantitative data for the NNMR have revealed regional scale patterns in sediment distribution not apparent in previous studies and have formed a framework within which local scale patterns can be understood in a regional context. Seabed sediments of the NNMR reflect present day oceanographic conditions and vary in proximity to sources of fluvial and terrigenous material. Sediments are composed of fine- to coarse-grained sand and mud, with carbonate content highest in areas with a high sand content such as the Joseph Bonaparte Gulf. The sedimentology of the Arafura and Sahul Shelves are distinguished from one another based on sediment texture and composition, as discussed below.

Our data indicates that seabed sediments of the Sahul Shelf are sand dominated with localised deposits of gravel on the inner shelf. Carbonate content is high due to the relict carbonate material and extensive outer shelf carbonate banks and facies that characterise the region (van Andel, 1965). Sediment distribution reflects oceanographic conditions and sediments fine with distance offshore. Our data supports the findings of Lees (1992) who described the sedimentology of the Bonaparte Gulf as grading from gravely sand and sandy gravel on the inner shelf to sand on the middle shelf and clayey sand on the outer shelf, a pattern that reflects a seaward decrease in tidal velocity (Lees, 1992).

The sedimentology of the Arafura Shelf, as described from our sediment data, is dominated by mud with localised accumulations of sand and gravel. Carbonate content is relatively low (mostly <20%) and increases towards the shelf edge/upper slope and with distance from sources of terrigenous input. This trend is consistent with Jongsma's (1974) sediment model of the Arafura Shelf which illustrates the high mud and low carbonate content of the middle shelf region. Our data quantitatively characterises the shelf break and slope beyond the Arafura Shelf for the first time, showing the region is sand dominated with small and localised gravel deposits.

6.3. IMPLICATIONS FOR MARINE HABITAT MAPPING

Conservation of benthic marine habitats requires information on the geomorphology, sedimentology and oceanography of an area. The use of sediment properties as physical surrogates for benthic biological data that can be measured with ease (Bax, 2001) and may provide a greater understanding of marine ecosystems (Post *et al.*, 2006 and Post, 2006). Relationships are recognised to exist between the texture and composition of seabed sediments and biota (Day, 2000; Kostylev, 2001; Roff, 2003; Roff, 2000). For this reason, sediment properties as measured in this study are an important input into statistical models used to approximate the nature and extent of seabed marine habitats (see the seascapes of Day and Roff, 2000). The accuracy of the seascapes in representing seabed habitats is directly related to the quality and resolution of underlying sediment data. Major sources of spatial error in sediment data used to characterise habitats are the result of low data density and inadequate interpolation methodologies. Addition of new data reduces these sources of error and allows recognition of relationships between physical datasets that are useful in developing more effective interpolation techniques.

Benthic biota have been shown to have measurable relationships with the gravel and mud content of seabed sediments (Post *et al.*, 2006; Bax, 2001). Our data show that where the sedimentology is relatively diverse, such as on the inner shelf and in submarine canyons, the sediment properties including gravel and mud content vary over relatively small distances. A much higher sample density is required in these environments to more accurately map the spatial distribution of the sediment properties (and by association benthic biota). Our data have improved sample coverage in these areas; however, additional coverage will further increase the reliability in which this can be mapped. In areas where seabed environments are relatively uniform, such as over most of the abyssal plain/deep ocean floor, sediment properties are more constant over larger distances and can be accurately mapped from fewer samples.

Our synthesis of sedimentology and geomorphology has; 1) provided a more comprehensive understanding of the range of seabed sedimentary environments present in the NWMR, 2) allowed comparison between sedimentary environments occurring in different areas culminating in the identification of rare or unique areas of seabed that may be of particular interest for conservation, and 3) described relationships between physical datasets providing full coverage of the NWMR, such as bathymetry and geomorphology, and sediment distribution. These can be used to predict the sedimentary environments that occur in areas where sediment data points are relatively scarce. New data on the abyssal plain/deep ocean floor have allowed characterisation at a higher confidence.

6.4. LIMITATIONS

Although we have added significant detail to the regional sedimentology of the northwest margin, including better defined local and regional trends, the data are still relatively sparse which limits the degree to which we can fully describe the sedimentology. It is important to recognise some of the limitations of the data.

Data in the NWMR is clustered around the middle shelf region, with a paucity of data located on the inner shelf and abyssal plain/deep ocean floor. This means that sediments present in areas with most data are likely to be overstated in descriptive statistics at a regional scale. Uneven distribution of data also makes it difficult to statistically quantify relationships that are observed visually in data and means that existing relationships may not be detected and utilised when interpolating data to rasters for input into seascapes processes. While this may cause some inaccuracy or bias at a regional scale, the structure of our analysis with observations and statistics generated for individual bioregions, provinces and features means that sedimentology at these scales is not significantly affected. Because data density is greatest on the middle to outer shelf we are confident that sediment patterns in this location are real. However, complexity elsewhere may not have been detected due to relatively low sample density.

In this study we have used the inverse distance weighted method with a fixed interpolation parameter, which has been used by Geoscience Australia to interpolate all of its point data across Australia's marine jurisdiction. This provides for a comparable and consistent dataset.

The maximum distance that any data were extrapolated was 45 km. This method is adequate, where large ranges in data density occur, to produce maps that allow identification of trends in sediment distribution occurring at a regional scale, but it is likely to inaccurately represent sediment distribution at finer scales.

The key question in modelling studies is "*How much simplification is acceptable?*" A linear inverse distance weighted method (with a fixed interpolation parameter) does not necessarily represent all trends in sediment distribution. However, no interpolation method is able to pick up such trends if sample density is inadequate. Trends in sediment distribution in the NWMR are known to occur on scales from centimeters to hundreds of kilometers. Without knowing at what scale variations in sediment characteristics are significant in mapping distribution of species, it is difficult to comment on how much uncertainty in interpolated data affects results generated for seabed habitat mapping.

Sample density for the NWMR is 1:700 km^2 on the shelf, 1:1,200 km^2 on the slope, 1:19,100 km^2 on the rise and 1:10,100 km^2 on the abyssal plain/deep ocean floor. This provides the minimum distances over which variations in the sediment properties can be detected. Interpolation images must be used with caution when drawing comparison between seabed composition in different areas of the NWMR as they do not necessarily; 1) represent the relative proportions of environments present in an area; or 2) the way sedimentary environments are interspersed spatially, as resolution of the interpolation is more a reflection of sample density than diverse sedimentology.

6.5. RECOMMENDATIONS

To improve interpolated data it is important to improve sample densities in areas of the seabed that contain significant variations in sediment characteristics over relatively small distances. As collecting sediment samples from the seabed is highly time consuming and costly, information about seabed complexity and the relationship to geomorphology can be used to target areas where data coverage is likely to be inadequate. New data generated for the NWMR and the SWMR (Potter, 2006) allow recognition of relationships between relatively diverse seabed sedimentology and geomorphic features including canyons and pinnacles. In the NWMR, sample densities in these features remain relatively low. New data for the NWMR also indicate that although sediments are more homogenous in deep water areas (e.g., abyssal plain/deep ocean floor), greater variation may be captured in these areas than is captured in the current data. Data generated for this study have significantly improved sample densities for these areas and this work should be continued, particularly for the abyssal plain/deep ocean floor, lower slope and rise.

Data collection, advances in interpolation methods, and improved understanding of relationships between geomorphic features and sediment type will improve the accuracy of future sedimentology work conducted at a regional marine planning area scale. An improved understanding of geomorphic features such as the abyssal plain/deep ocean floor is required to most accurately map sediment distribution. Where sample coverage is sparse, the inclusion of secondary datasets in the interpolation process will allow the prediction of sediment type. Secondary datasets such as energy level, tidal regime, sediment transport pathways, and previous sediment models will improve the accuracy of future seabed sediment mapping. Our study has shown that future sampling in the NWMR should focus on areas with poor sample coverage such as the abyssal plain/deep ocean floor, pinnacles, trenches, inner shelf, lower slope and rise.

Geoscience Australia has a research program to assess the accuracy and precision of interpolation techniques and is investigating the usefulness of secondary datasets during interpolation.

6.6. SUMMARY

The NWMR and NNMR are characterised by a variable geomorphology and sedimentology. Sediment texture and composition displays a zoning with depth, and sand and gravel dominate the shelf area whilst mud dominates the lower slope and abyssal plain/deep ocean floor. Calcium carbonate concentrations throughout the region are generally highest along the shelf to the shelf edge and are associated with reefs. Significant geomorphic features of the NWMR and NNMR include; pinnacles, shallow water and deep water terraces, slope, rise, trenches/troughs, shallow water and deep water plateaus, deeps/holes/valleys, slope, shelf and banks/shoals of the Joseph Bonaparte Gulf.

Geoscience data plays a vital role in the management of Australia's ocean resources because we may never have a full inventory of all biota found on the seabed particularly for deep sea regions. Geomorphology and sedimentology data can be mapped economically and the data can be used to infer relationships between the distribution and abundance of benthic biota. The relationship(s) between geomorphology and sediment/substrate type and biota is a key priority for research associated with the implementation of Bioregional Marine Planning Areas.