Government of **Western Australia**
Department of **Mines and Petroleum**

# Migration of limesand dunes in Western Australia and their impacts

## Implications of a geohazard along the Mid West coast of Western Australia

By Josefine Bruch and Michael Freeman

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February 2017

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**REFERENCE**

**The recommended reference for this publication is:**
Bruch, J., and Freeman, M.J, 2017, Migration of limesand dunes in Western Australia and their impacts:
Department of Mines and Petroleum, Perth, Western Australia, report, 2017

National Library of Australia Cataloguing-in-Publication entry

| | |
|---|---|
| **Creator:** | Bruch, Josefine, author |
| **Title:** | Migration of limesand dunes in Western Australia and their impacts : implications of a geohazard along the Mid West coast of Western Australia / Josefine Bruch, Michael Freeman |
| **ISBN:** | 9780646963419 (ebook) |
| **Subjects:** | Subjects: Sand dunes – Western Australia.<br>Sand dune management – Western Australia.<br>Coastal zone management – Western Australia.<br>Shore protection – Western Australia.<br>Geomorphology – Western Australia. |
| **Other Creators/ Contributors:** | Freeman, Michael John, 1946-, author |


**About this publication**

This report represents the results of research by the Department of Mines and Petroleum on the mobility of certain sand dunes along the Mid West coast of Western Australia, between Perth and Geraldton. The Department is releasing the report to ensure a wider distribution of the results, which includes the characterisation of sand dunes and documentation of their rates and directions of travel during the period 1960 to 2010 and interpretations.



**Published 2017 by Department of Mines and Petroleum, Western Australia**

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## Preface

This report was compiled by Josefine Bruch, from Dresden University, Germany, as a geomorphological study on the movement of several sand dunes on the Mid West coastal belt of Western Australia. Ms Bruch was assisted with much guidance, support and definitions of concepts by Mr Bob Gozzard of the Geological Survey of Western Australia.

The task was completed as an internship during a three-month period in late 2011 when Ms Bruch was sponsored jointly by the Mineral Titles Division of the Department of Mines and Petroleum and the International Association for the Exchange of Students for Technical Experience (IAESTE). IAESTE is the largest student exchange organisation worldwide, providing high quality practical training for tertiary students in foreign countries. Founded in 1948, it describes itself as a non-political, independent, non-governmental organisation which maintains consultative and operational relationships with agencies of the UN such as the United Nations Educational, Scientific, Cultural Organisation (UNESCO) or the United National Industrial Development Organization (UNIDO).

This report was initially drafted in 2011 but was revised by the second author during 2014–15 to use more non-scientific language to be in keeping with the needs of the inferred audience likely to read the document and to use the information. In addition, amendments, changes and expansion of the interpretations were carried out to improve the readability and organisation of the report. Google Earth images of the latest (2015–16) scenes replaced earlier images to present the latest situation of the dunes.

## Summary

This report is a documentation of the rates and directions of migration of limesand dunes in parts of Western Australia. With the application of ArcGIS, georeferenced maps and aerial images from 1960 to 2010 were used to measure and monitor the locations of a selection of mobile dunes along the Mid West coast between Lancelin and Geraldton. Over the period of the study those measured travelled at rates that averaged between 4.1 and 15.8 metres a year for the 50 years, generally moving in a northerly direction, covering between 20,000 and 14 hectares and the longest migration distance identified is 21 kilometres. The monitoring of migration rates can provide valuable information for resource management and geohazard risk reduction as the rates and directions measured can provide predictive tools to document future impacts on built infrastructure. Therefore this report analyses factors that can influence the migration rate and direction of dunes such as climate data, dune

morphology, sediment supply and human activity. The main factors which influence the presence of mobile sand dunes in Western Australia are the wind regime and sediment supply. The study also discusses solutions to stabilise dunes in coastal areas. However, because of the vagaries of natural processes, no prediction of impact dates or severity presented herein are to be taken as fixed or firm. Any users of the data or suggested times or severity of impacts must undertake their own specific studies if definite predictions are required.

Built infrastructure in general had initially been constructed remote from mobile dunes. However, in the decades since construction, the dunes continued migrating and in a number of cases will pose threats to infrastructure. Several of those dunes considered to pose such threats were studied, along with a few others to give better representation of their movements.

It was also concluded that the speeds determined for those dunes included in this study are probably reliable long-term indicators of the rates, but are not reliable on shorter time frames, such as over a decade interval.

The coast and the locus of coastal developments trend parallel to the main winds that mobilise dune sands. This has major implications for land use and development planning because it exposes the maximum number of sites to the geohazard of migrating dunes. Anything built north of and within a close distance of an existing mobile dune near to the coast is likely to eventually become threatened.

The sand mainly consists of sand-sized limestone grains. This limesand is useful for combating increasing acidity in farm soils and is therefore in demand for use through the Wheatbelt region of Western Australia. Physical actions to stop a dune blowing over infrastructure, such as removing the sand with machinery, could be very expensive. Local communities are unlikely to be able to fund such activities without straining local budgets. However, the limesand itself has an economic value when applied to farmland. Therefore, marketing of the limesand from threatening dunes is highly recommended in order to utilise the value of the resource to pay for reducing or removing their threats.

The conclusions for each of the dunes studied follow, commencing at the northern-most dune and progressing southward:

- The Southgate Dune has a total area of 139ha, is moving northwards in the direction of the community of Wandina and will soon blow sand into the housing areas as it is only 230m away. South of this sand dune is the Greenough River mouth which probably supplied sand for the development of the dune. Extraction of limesand from the head of the dune is proceeding and it is recommended that the rate of production be monitored in order to stop the head migrating towards the houses. From the data available it is considered that the order of 25,000$m^3$ (cubic metres) of limesand needs removing at the dune front each year to minimise the forward movement of the dune.

- The Cape Burney sand dune is situated 420m south of the Greenough River mouth. This limesand dune has a total area of 60ha, is moving in a north-northwesterly direction and will soon blow sand into the Greenough River. Blockage of the river may then ensue although if river flows are strong enough it may maintain its course rather than be blocked. It is recommended that the potential problems that might arise from either scenario be considered by the local authority.

- The third area of sand dunes studied southwards is located 8km south of Dongara where dunes are blowing out of the Beekeepers Nature Reserve onto other land tenures. This area contains several discrete dunes, although only two were studied that are moving north-northeasterly and one is currently blowing over Kailis Drive. The sand dunes are named Dongara West, with a total area of 20ha and Dongara East with a total area of 13ha. Dongara West intersected Kailis Drive in the early 2000s and ongoing Shire-facilitated remediation is reportedly in place, though with time the higher parts of the dune will arrive at the roadside and constitute greater difficulties requiring consideration and attention. A mining lease recently granted could facilitate extraction of limesand from the head of the dune to reduce the potential impacts of the migration as the sand blows out of the adjacent Beekeepers Nature Reserve.

- The next dune area studied southward comprises four mobile limesand dunes grouped under the name of the White Point dunes. These sand dunes are located within the Beekeepers Nature Reserve southwest of the Dongara-Eneabba-Railway. The sand dunes are moving north-northeasterly in the direction of the railway line and in a few years they will intersect it. The nose of the largest sand dune in this area is White Point, which is up to 18m high with a total area of 118ha, and is only 750m from the railway. Monitoring of the movement is recommended along with planning on future actions to minimise impacts.

- Illawong Dune, located immediately west of Indian Ocean Drive has a crest up to 4m high and a total area of 111ha. This dune is about 1000m from Indian Ocean Drive. Measured along the trend of its movement and at the 1960–2010 average speed of 9.4m/year it has been estimated to take over 75 years for the dune to intersect the road. However in the period 2001–10 it averaged 30.4m/year and at that rate it will cut the road in 33 years. Monitoring of the movement is recommended to allow for early planning to minimise impacts.

- Coolimba was previously one dune but has separated into two dunes. The western dune, the larger of the two, has an area of 71ha and is located north of the Coolimba-coastal settlement. It has migrated approximately 2.5km north-northeasterly since leaving the beach head and is now closer than 500m to the Indian Ocean Drive and the Beekeepers Nature Reserve. The smaller dune has an area of 9ha and appears that it is being well-colonised with vegetation and may stop moving in the next few years. Extraction of limesand is ongoing from behind the head of the larger dune that will probably reduce its velocity, if not stop the dune. It is concluded this dune poses no immediate threat to the highway but should be assessed about 2050 to ascertain if that is a possibility.

- The next sand dunes southward in the study area are situated near the town of Green Head. The fast moving sand dune, named Green Head North, has a crest height of 3m, is located 2km north of the town and has an area of 28ha. The larger second sand dune, Green Head South, is up to 4m high, is located 4km south of the town of Green Head and has a total area of 191ha. Both mobile sand dunes are moving northwards, and Green Head North dune is less than 150m from a well-used scenic access road to coastal bays and is frequented by tourists. Grant of a mining lease and mining approval to permit extraction of the limesand is recommended to avoid the dune crossing and blocking this road. Green Head South could have impacts upon Indian Ocean Drive as the nose of the limesand dune is only 350-500m away from the highway. Mining Lease 70/782 exists over Green Head South and extraction of the limesand may result in the dune stopping before it reaches the highway. However it is considered that the movement needs monitoring in case the dune still migrates to the highway.

- The sand dune area Sandy Cape used to be one large dune migrating from the south but split into two dunes between 1982 and 2002. The larger eastern sand dune is 80ha in area and has already blown across the access track to Sandy Point. Consequently that road was closed and a new road was built south of the sand dune to access the coast. The smaller western dune appears to be becoming stabilised with vegetation colonising it. No action is recommended.

- The large Grey sand dune (370ha) located in the Nambung National Park and less than 600m northeast of the former coastal settlement of Grey, was blowing sand north-northwesterly over the route of the Indian Ocean Drive before road construction started. Main Roads WA removed sand from a 100 metre-wide strip next to the road alignment before construction commenced and it was revegetated as part of the road construction. This section of the Indian Ocean Drive was opened to the public in 2010 but since then the main bulk of the dune has continued migrating northward. The nearest part of the dune is 400m from blowing over the highway and with the peak of the dune having a height of over 10m, it will pose a significant problem when it reaches the road. It is recommended that this needs consideration and planning to cope with the limesand problem.

- The sand dune area of Wedge Island comprises three mobile dunes which are moving in a northerly and north-northwesterly direction. The dune Wedge Island East is less than 1km away from Indian Ocean Drive and will potentially have a major impact on this road, although it will be decades before that occurs. Wedge Island East is the biggest sand dune of the study area with a total area of 1005ha. This dune is moving into the Wanagarren Nature Reserve from the Commonwealth defence leasehold land of Lancelin. Wedge Island South has an area of 113ha and is possibly going to blow sand over the coastal access road to the beach shacks of Wedge Island as it is currently only 200m southeast of the road, although the sand is blowing into a broad vegetated depression and may halt before intersecting the road. The sand dunes Wedge Island South and East used to be one dune that separated in the decade between 1972 and 1982. Wedge Island North, which has an area of 463ha and a height of 5m, is migrating north-westerly and back into the ocean and does not pose any risks. It is recommended that migration of East and South dunes be monitored in order to plan for future remediation should it become necessary.

- The Lancelin dune is the southern-most studied. This large sheet-dune was migrating at the fast rate of 38m/year during the first period studied (1960–82), but slowed to 10.7m/year in the second period (1982–2004) and then to 6.1m/year in the third period (2004–10). Simultaneously it decreased in area from 1070ha in 1960 to 674ha in 2010. Extraction of limesand from a mining lease at the southern end of the dune correlates in part with this decrease in velocity and area and it is considered likely that this mining resulted in a significant degree of stabilisation of the dune movement. The southern parts of this dune sheet previously had the potential to expose houses on the eastern margin of the townsite to a threat of being impacted. However, it now appears this threat no longer exists.

# Introduction

Sand dunes can be found along coastlines worldwide. When located along the coast away from human activities, they don't have a negative impact on human welfare and aren't considered to be a geohazard. In fact sand dunes can even have positive impacts as they provide shelter to the immediate inland areas from storms and flooding sea-level rises and can ameliorate onshore storm winds. However it is critical to be aware of the consequences when sand dunes became mobile and migrate, blowing over infrastructure such as roads, settlements and other developments.

The aim of this report was to document the migration of several sand dunes along coastal parts of Western Australia using ArcGIS, georeferenced maps and aerial images. The monitoring of dune migration rates can provide valuable information for resource management and geohazard risk reduction. This report provides an analysis of various factors which can influence the migration rate of dunes. Climate data, such as temperature, rainfall and wind were analysed in conjunction with dune morphology and sediment supply to ascertain why the sand dunes migrate inland, in which direction they are most likely to travel and at what rate. With the assistance of Mr Bob Gozzard, Senior Geologist in the Geological Survey of Western Australia, the outline of the dunes at various times over 50 years in the study area was analysed and mapped using the computer program ArcGIS. Following this, a study of other available material such as the climate and vegetation data of Western Australia was completed. This data was then organised into tables and charts which allowed conclusions to be made in respect to climate, vegetation cover, sediment supply and human activity all influencing the migration of mobile sand dunes which can have dramatic impacts on the surrounding infrastructure and environment.

In 2011 Damara WA Pty Ltd, in collaboration with the Geological Survey of Western Australia, undertook research into the vulnerability of coastlines by studying wind patterns and sea conditions along WA's Mid West coast (Stul et al, 2012) for the Department of Transport. That study focuses on the offshore and coastal zone and its assessments and conclusions have relationships to this sand dune study.

The research undertaken in this study and reported in this present document leads to recommendations regarding measures that could be taken to monitor, conserve and preserve the dunes while simultaneously preventing further destruction and damage to infrastructure in Western Australia.

# Study area, setting and overview

The study area for this report is approximately 265km long and 5km wide, stretching along the WA coastline from Geraldton to Lancelin between 360km and 110km north of Perth (Figure 1). The study focuses on 12 identified sand dunes or groups of dunes, several of which are impacting or may impact various infrastructure or conservation areas. However, there are many more dunes that were not studied and mobilisation of dunes that are currently stable or initiation of new blowouts from the coastal dunes may lead to new geohazards developing. From assessing the images, it is obvious that the mobile dunes have been blowing along the coastal zone possibly since the Pliocene times (about 5 million years ago). There is no reason to consider the process of initiating dunes migrating along the coastal zone has ceased.

A number of towns and other coastal settlements exist within the study area. There are two Nature Reserves, Beekeepers and Wanagarren, Nambung National Park, a number of reserves vested in Local Government authorities intended to allow for locally-managed coastal living and recreational pursuits and a small number of freehold titles. The aim of the conservation reserves is to conserve their natural biological asset and biodiversity and cultural heritage (TasGov, 2011). Nambung contains the Pinnacles Desert a popular tourist feature that is based on unusual limestone pinnacles (Lipar and Webb, 2014) that is on the State Geoheritage Register. Between the two southern-most dunes is an extensive area of leasehold and freehold land in the name of the Commonwealth Government that is utilised for defence training purposes and contains one of the largest sand dunes along the Mid West coast.

Geologically the dunes in the study area are modern coastal sand dunes located within the Perth Basin. The Perth Basin is a tectonic unit extending northwards for approximately 700km from the south coast of the State along the western coastline. It is bounded on the eastern side by the Darling Fault and consists of up to 15,000m of sediments ranging in age from Permian to Holocene (300 million years [Ma] to the present). The basement rocks under the Perth Basin, referred to as the Pinjarra Orogen, consist of igneous and metamorphic rocks with minor areas of sedimentary rocks and have a Proterozoic age ranging from 1300 to 900Ma.

This study focuses on the youngest sediments of the Perth Basin consisting of various sand and limestone units. The geological units are related to physiographic or geomorphological units. The nearshore Safety Bay Sands underlie the Quindalup Dunes. The Safety Bay Sand is Holocene in age (<12 000 years) and includes the modern mobile sand dunes immediately along the shoreline (Abeysinghe 1998; Sanderson and Elliott 1999 and Semeniuk 1988). Inland of these dunes is the Spearwood Dune system underlain by both limestone of the Tamala Limestone and sand derived from the Tamala Limestone. Further inland again is the Bassendean Sand that underlies the Bassendean Dunes. These dune or sand units grade easterly into a more silt or clay-rich unit, the Guildford Formation that underlies the Pinjarra Plain. This unit laps against the Darling Scarp and the Gingin Scarp as well as underlying the sand units.

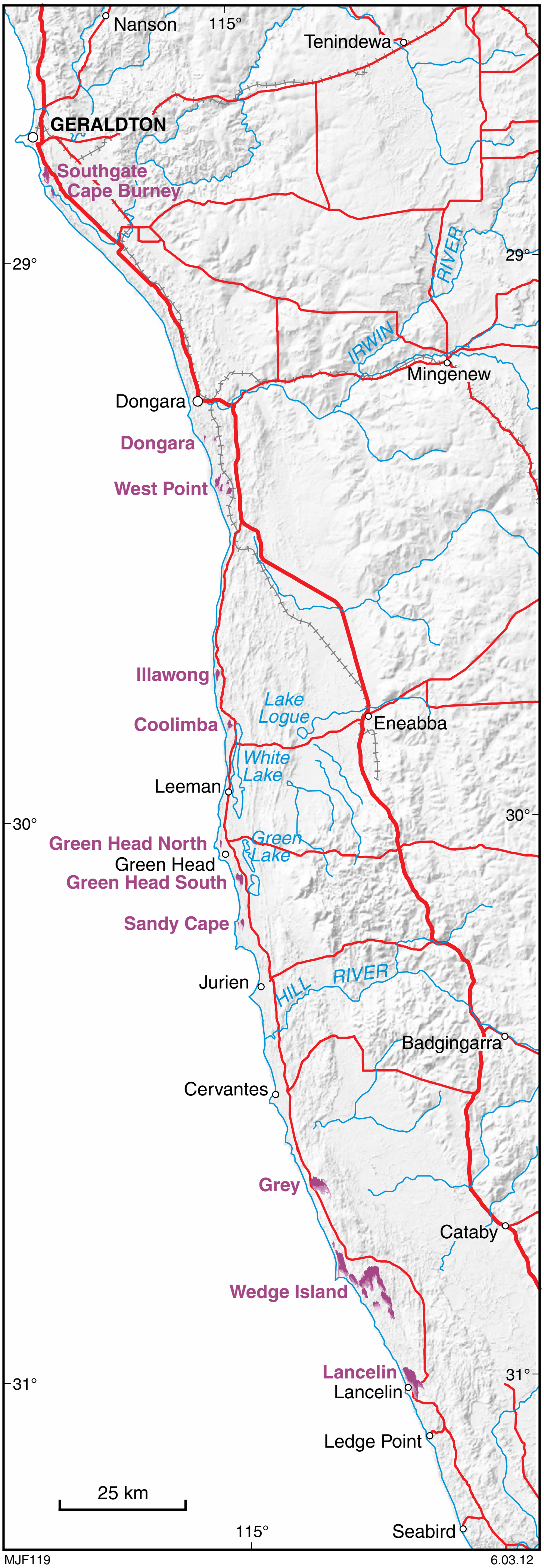
Both the Safety Bay Sand and the Tamala Limestone consist of medium to coarse-grained calcareous sand, quartz sand, limestone consisting of cemented calcareous grains, and calcareous sandstone. The age of the Tamala Limestone is late Pleistocene (ranging between 2.6Ma and 12,000a). The sand-sized sediment grains are almost all originally shell and other biogenic fragments with minor amounts of quartz sand. The shell fragments were formed by the breakdown of sea shells through wave action pulverising the biogenic remnants on or adjacent to beaches.

The modern mobile coastal dunes vary in volume and general physiography and are dependent on the nature of the coastal type and sediment supply. More dunes exist in the middle of the study area than in the south, inferred to be due to the higher aridity and stronger wind regime towards that portion. However, in the north the dunes between Dongara and Geraldton form a noticeably narrower zone. It is inferred that this may reflect the paucity or absence of offshore reefs and the relationship between the trend of the coast and the angle subtended between the coastline and the direction of the dominant winds.

The Holocene dunes overlap the Pleistocene units and therefore Semeniuk (1988) describes it as a “coast to hinterland” relationship. There exists a relationship between coastal facies, which comprise calcareous marine and eolian sediments, and continental facies which consist of eolian quartz sand with a transition between both (Semeniuk 1988) as shown diagrammatically in Figure 2.

Dune sand with a high content of lime (calcium carbonate) has a premium commercial market value through being supplied to farmers for application to farmland to reduce the build-up of acidity in agricultural soils (EPA 2006).

Figure 1. Study area and names applied to dunes as shown by the purple shapes.



## Study methods

The main data used in this study was taken from historical and current aerial photographs (airphotos), historical documentary information, topographic maps, tourist-type maps (scale 1:400 000) and Google Earth images, all of which depict a record of dune morphology and migration. The scale of the aerial photographs supplied depends upon the year in which they were taken as well as the area and the survey. For example, in the Perth and Hill River area the scale is 1:50 000 whereas in Dongara it is 1:25 000. The photographs were taken across numerous years between 1960 and 2010. A map also exists for the Green Head to Wedge Island area dating back to 1910 and was drawn by Campbell (Figure 3; Campbell 1910).

The images were digitised and corrected by adjusting the projection, perspective and scale to ensure the data compiled was conducted on comparable images. The aerial photographs were not always taken from the same location and therefore required standardisation of the projection and perspective and to correct the distortion. After all the images were digitised by scanning they were further processed using ArcGIS/ArcMap software.

The airphoto flying was conducted as a series of surveys covering different parts of the study area at different dates. Consequently there are gaps in the data record through this lack of integrated flying of the total area. Some of the gaps were overcome by including nearby airphotos of a slightly different time and allowances were made on the interpretations. Through this interpretive process a much more complete assemblage of results was achieved. The scanned photographs were compiled into ArcGIS's subprogram system ArcMap to be georeferenced utilising current mapping by comparing the digital photograph with fixed locality features on the modern map, such as road intersections, buildings and other features that were identifiable on both images. The next step was mapping the movement of the sand dunes in ArcMap by analysing the aerial photographs for each available year. Each sand dune used for the research had to be mapped at least once in each decade. The outlines of the sand areas were drawn using the ArcGIS polygon feature tool. In a number of cases, vegetation exists within the sand dune areas and therefore the polygons became donut shaped. In these the vegetation areas had to be removed by using the clip tool of the Editor and then converted to lines and smoothed using the XtoolsPro program for a better result. Using the measuring tool of ArcGIS, the average rate of migration of the sand dunes as well as the total area of each dune in each year could be measured. To draw the correct outline of the sand dune the DEM of the area was analysed as well as the vegetation cover surrounding each dune. With both elements it was possible to define the sand dune outline for each year. The results are represented in maps in the Appendices. Figure 4 shows an example of the outcome of the processing for one dune.

The dunes specifically studied were named based on a nearby feature or town (Table 1 and Figure 1). The dunes occur in a number of Local Government Areas as listed in Table 1 along with the latitude and longitude of each dune or group of dunes studied.

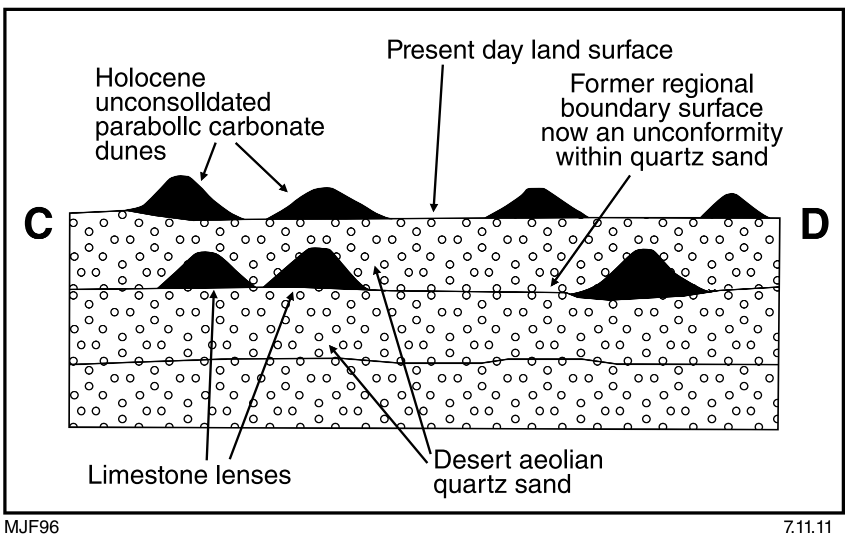



**Figure 2. Hypothetical section showing typical Units in the study area (Semeniuk 1988)**

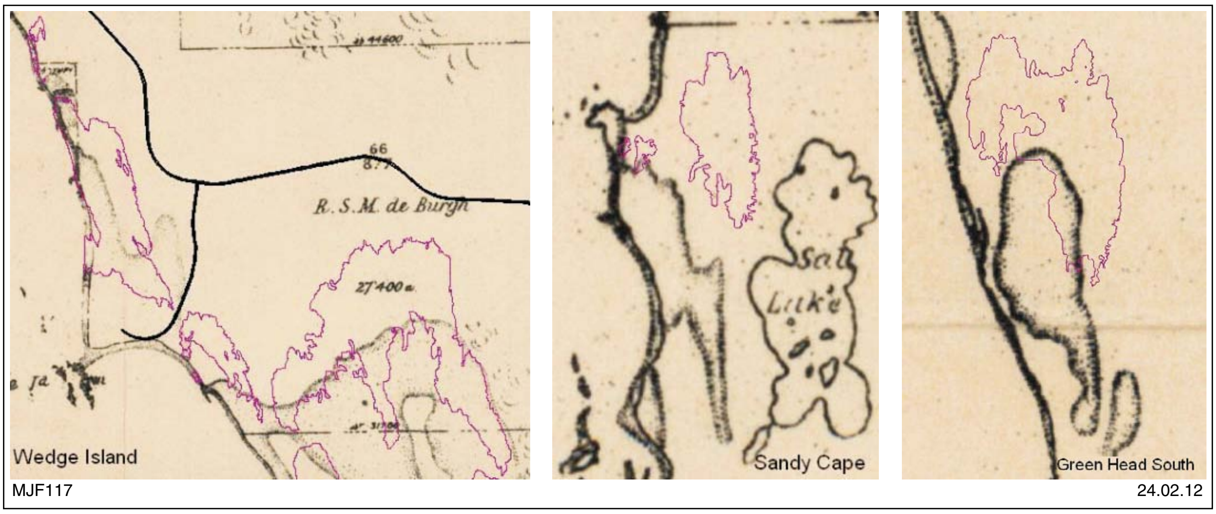



Figure 3. Comparison between sand dunes of 1910 (Campbell 1910, black lines) and 2008–10 (ArcGIS, violet lines)

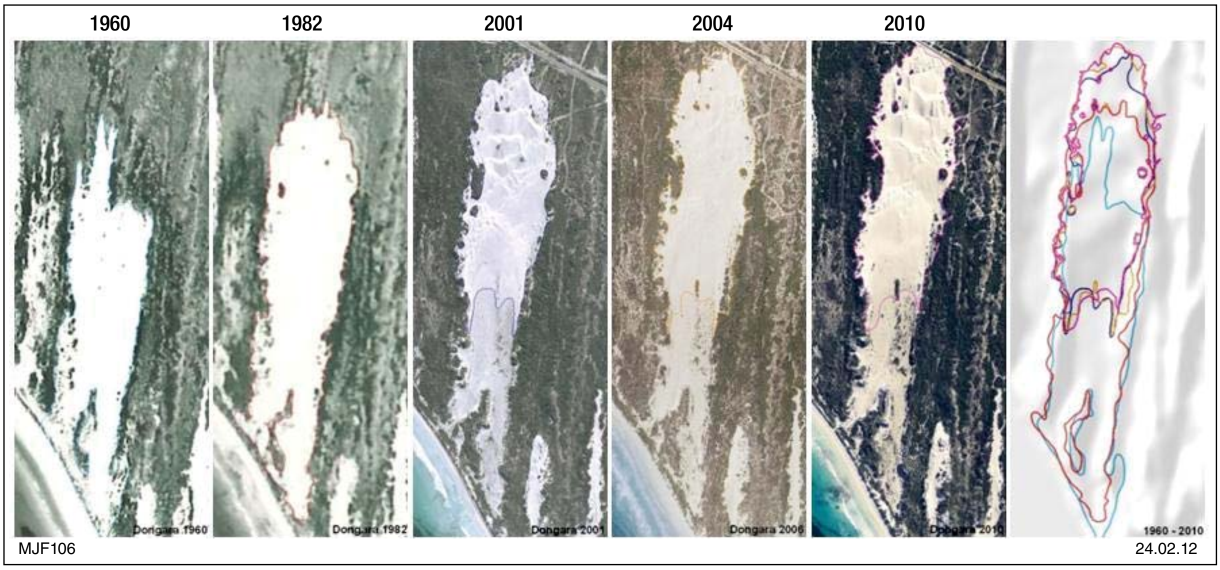



Figure 4. Example of one dune showing the nature of the shape and area change during migration of a sand dune between 1960 and 2010 with the illustration on the right-hand side showing how those changes were represented in ArcGIS

## Dune morphology

A sand dune is a ridge or hill of sand created by winds and can be differentiated depending on whether it is located near an ocean, lake or in a desert. To classify the dunes in the study area it is important to differentiate between coastal dunes and desert dunes. Coastal dunes will generally only have sediment supply from off the shore or beach and will be driven dominantly by onshore prevailing winds. Dunes in the desert are not limited by the availability of sediment from one source because the sand supply is available from any wind direction and therefore the wind pattern is the primary factor influencing desert dunes. Dunes adjacent to lakes or playas have specific shapes and sizes governed by the attributes of the specific site.

**Table 1. Dune names, relevant local Government responsible for area and location**

| DUNE | LOCAL GOVERNMENT AREA | APPROXIMATE CENTROID | |
|---|---|---|---|
| | | LATITUDE South | LONGITUDE East |
| Southgate | City of Greater Geraldton | 28° 50’ 12” | 114° 37’ 50” |
| Cape Burney | City of Greater Geraldton | 28° 52’ 16” | 114° 38’ 42” |
| Dongara West | Shire of Irwin | 29° 18’ 56” | 114° 56’ 40” |
| Dongara East | Shire of Irwin | 29° 19’ 12” | 114° 57’ 56” |
| White Point | Shire of Irwin | 29° 24’ 07” | 114° 58’ 58” |
| Illawong | Shire of Carnamah | 29° 44’ 23” | 114° 57’ 44” |
| Coolimba West | Shire of Carnamah | 29° 49’ 44” | 114° 59’ 06” |
| Coolimba East | Shire of Carnamah | 29° 49’ 58” | 114° 59’ 22” |
| Green Head North | Shire of Coorow | 30° 2’ 34” | 114° 57’ 43” |
| Green Head South | Shire of Coorow | 30° 5’ 55” | 115° 00’ 02” |
| Sandy Cape | Shire of Dandaragan | 30° 10’ 47” | 115° 00’ 15” |
| Grey | Shire of Dandaragan | 30° 38’ 57 | 115° 08’ 48” |
| Wedge Island North | Shire of Dandaragan | 30° 47’ 33 | 115° 11’ 49” |
| Wedge Island South | Shire of Dandaragan | 30° 49’ 16 | 115° 13” 14” |
| Wedge Island East | Shire of Dandaragan | 30° 48’ 40” | 115° 15’ 37” |
| Lancelin | Shire of Gingin | 31° 00’ 04” | 115° 20’ 39 |

*As in many references to the dunes in this study report, the names are in geographical sequence from north to south.*

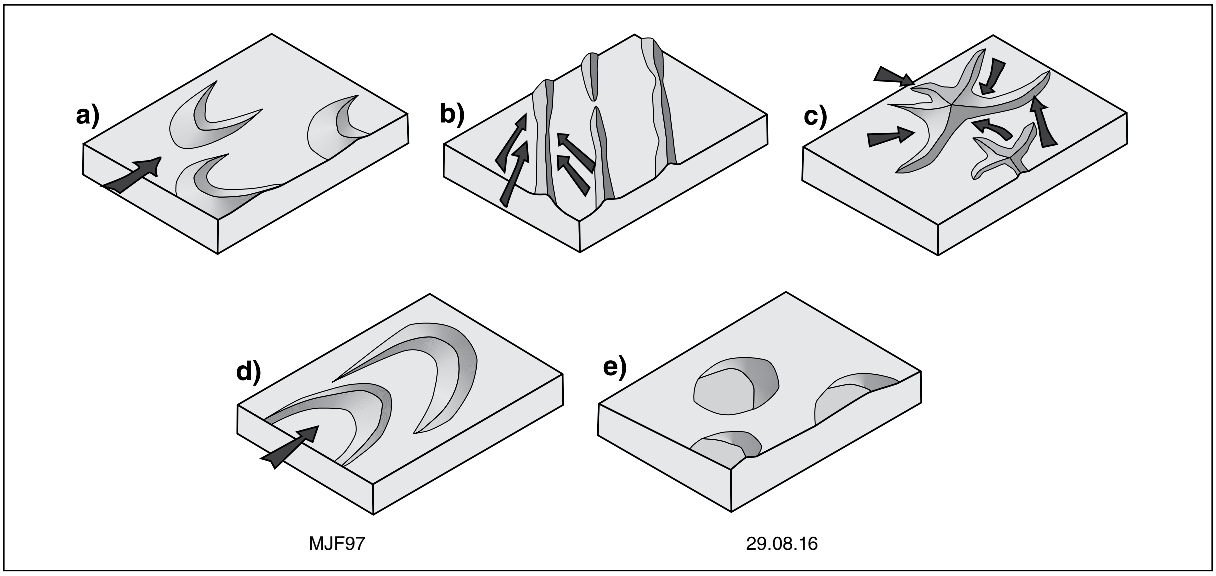



**Figure 5. Dune forms (from Short & Nicholas, 2011)**

The United States Geological Survey (USGS) classifies five transgressive dune types as below and as shown in Figure 5.

(a) crescentic (barchan)
(b) linear
(c) star
(d) parabolic
(e) dome.

In addition, extensive areas or sheets of sand may migrate across the countryside with a range of dunes types on top of the sand sheet. These transgressive sand sheets can cover very large areas in continental dunefields and migrate at slow to fast speeds depending on the nature of prevailing winds. Moderate-sized transgressive sand sheets occur at Lancelin and Wedge Island and a smaller sheet at Cape Burney-Southgate.

Across the various types of dunes the migration velocity ranges from fast to slow and the velocity can vary markedly within a single dune. A crescentic or **barchan dune** (Figure 5a) is wider than it is long with fast moving arms and migrates more rapidly than other dune types. **Linear dunes** (Figure 5b) are longer than they are wide with prominent snakelike ridges. Linear dunes do not migrate; they get longer over time, often up to several kilometres. **Star dunes** (Figure 5c) are the tallest dune type reaching over 100m. These have arms radiating out from the centre formed by the winds which blow from more than three directions and are therefore relatively immobile. **Parabolic dunes** (Figure 5d) look similar to barchan dunes but with arms that follow behind the crest point. Vegetation grows on the arms of the parabolic dune, holding them in place while the body of the dune migrates forward (Ronca 2011). The shape of a parabolic dune changes with the dune becoming longer over time. A **dome dune** (Figure 5e) is circular and these are very rare.

In addition to the USGS classification, there are numerous opinions on how to classify dunes. Girardi (2005) and McKee (1979) classify dunes according to their complexity although their focus seems to relate more to desert dunes than coastal dunes. Their first classification is simple dunes, which have an isolated body with no contact with other dunes in the area. This dune type is common in areas where there is only one dominant wind. Examples of simple dunes are barchan, parabolic and transverse dunes. Their second classification is compound dunes which are multiple dunes of the same type overlapping – eg. star or barchan dunes. The third classification is complex dunes where two different dune types are growing together – eg. blowouts on a transverse dune.

It is not as appropriate to classify coastal dunes in the same manner as desert dunes. The growth of coastal dunes is limited by the sediment availability and the fact that the sand only comes from one main direction, from the beaches. Coastal dunes are strongly influenced by wind, vegetation and moisture, and they always form in the direction the wind is dominantly blowing. At the beginning of the development of the dune the shape is constrained by that of the coast or beach. However, coastal dunes are very sensitive to any change in sediment supply, wind regime or rainfall, especially as those factors can later change the outline and morphology of the dune (McKee 1979).

# Mobile sand dunes

The mineral composition of the sand dunes in the study area ranges from limesand to quartz sand. The chemical composition ranges from calcium carbonate-rich to silica-rich. Near-coastal sand is lime-dominant, but the concentration of lime, in general terms, becomes lower progressing inland and the Bassendean Dunes dominantly consist of quartz sand. However, this study has concentrated on the lime-rich mobile dunes within the Quindalup Dune System. Magnesium carbonate occurs in minor to trace amounts with the calcium carbonate. The sands consist of bleached white, yellow, beige, red and grey shell fragments of marine organism (Figure 6 and Figure 7) with grain sizes ranging between 0.4mm and 2.6mm (2.64 – 0.684 Φ[1]; Sanderson and Elliott (1999)). The shell fragments are of Pleistocene to Holocene age (less than 2.6 million years; Bird 1984). The coast of Western Australia has a long length of irregular coastal dune topography, and Bird (1984) suggests limesand dunes were probably formed when the sea level was lower and the sand was blown from what is now the sea floor potentially increasing the complexity of the coastal morphology. However, dunes appear to be forming at today's sea level (for example north of Jurien Bay), arguing against this interpretation.

Bird (1984) inferred that a small tidal range, for example as along the west coast of Australia, results in the sand being delivered to the beach primarily by wave action with tidal range being less important for accumulating the sand on beaches. This is in contrast to coastlines with larger tidal range that allow for greater drying of sand at low-tide times, potentially having a significant control on the rate at which dry sand is blown to form foredunes.

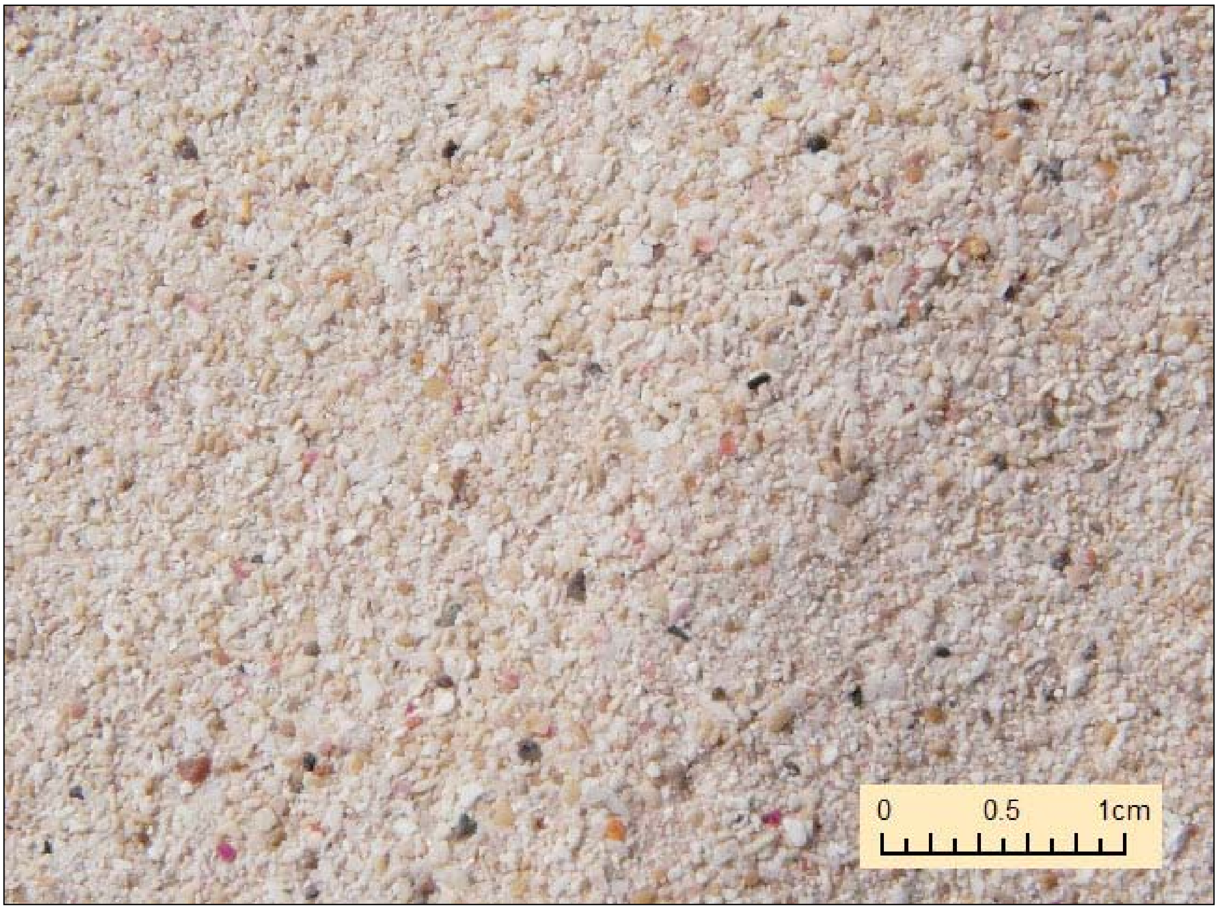



**Figure 6. Sea shell fragments in the limesand dune at Lancelin have a particle size of sand typically less than 0.5mm. This is a later stage in comminuting the sediment particles, having undergone a greater degree of wind and water transportation that reduces the grain size as they are carried along.**

1 The Phi (Φ) Scale (defined as the grain size to the $-\log_2$ [diameter in mm]), was conceived by William Krumbein (1934) and is a system of measuring sediment grain sizes. It is useful in that the larger the number, the finer the grains and hence easier to transport. The system can be applied to dune sands as well as the more normal application to alluvial transported sediments. The basic concept is that the Φ size increases as the grain size decreases and is a useful alternative to simply quoting dimensions. 2.64 Φ to 0.684 Φ are equivalent to 0.37 to 1.46 mm which is defined as fine sand to coarse sand using the terminology of Wentworth (1922)

**Figure 7. Sea shells that have been partially pulverised by beach and dune processes. The largest fragments are up to 2cm across. This is an earlier stage in comminuting the shells than in Figure 6 (pocket knife is 9cm long) as the fragments have been transported shorter distances and have not been ground down to the same degree.**

Once a foredune is built up at the back of the beach by eolian movement, vegetation can become established on it and this traps further blowing sand. Trapping grains enhances the foredune, building it up in height and broadening it as the sand accumulates. The native vegetation dune pioneers on the West Australian coast are dominated by coast fescue (*Festuca littoralis*) and sand spinifex (*Spinifex hirsutus*).

Subsequently cliffed foredunes form when the seaward side of the foredune is eroded or trimmed back by waves in response to higher than usual sea levels, potentially in response to storm surge. The new sand supply from the erosion can lead to the growth of a new foredune at the foot of the eroded dune. Due to this effect the sand builds up a new beach ridge parallel to the foredune and a little further towards the ocean. Again, with the colonisation of vegetation on the new beach ridge the blown sand becomes trapped and a new foredune is established. The old foredune then becomes stable and a vegetation succession starts. With time the dune grass is replaced by scrub vegetation and the vegetation succession in the near-shore environment ends with woodland or heath. Where this process repeats itself several times, a series of parallel dunes will be created (Figure 8). The parallel dunes are separated by swales (Bird 1984).

Storm winds can remove the pioneer vegetation cover allowing erosion of the foredune and thereby exposing the more-inland climax vegetation[2] to higher wind stress which can cause further sand destabilisation and concomitant removal of the more mature vegetation. The Department of Environment (Beach Protection Authority, Queensland; not dated) quoted that human activity, grazing, rabbits or a phase of aridity, droughts and fire can also cause the removal of vegetation cover from the foredune. Once this occurs, the lowered vegetation density does not protect the dune, the sand starts moving in masses and, as the foredune ridge becomes unstable, strong onshore winds can erode at a gap in the foredune and develop blowouts, (DERM, 2011). Strong onshore winds can then blow the sand landwards (Figure 9).

[2] Climax vegetation is the association of plants that results when they evolve to colonise an area following some significant environmental change. In the sand dune case, it is the plant association that is the final occupier after a mobile dune is colonised and stabilised.

The shore-parallel dune ridges then locally develop into migrating patches of sand. Commonly, as these patches start to migrate, they become parabolic dunes. This occurs because onshore winds typically cause the nose of the parabolic dune to travel faster than the outer parts which are held back by vegetation and by slightly lower wind velocities. The dunes then develop trailing arms and therefore a parallel dune has the potential to become a parabolic dune migrating inland at an angle to the shore-parallel dunes. While this angle is commonly referred to as being high in many situations, along the Mid West coast, the angle may be as low as 10°. In other words, the blowout is migrating nearly parallel to the shore-line trend.

The movement of the sand dunes is influenced by the direction, frequency and strength of the onshore winds. The nose of the parabolic dune moves parallel to the direction of the onshore winds. The dunes migrate when the wind moves the sand by creep (also referred to as reptation), saltation or suspension movement up the windward slope and over the crest of the dune, and the sand then accumulates on the slip face. Wind strengths required to move dune sands are measured on the Beaufort Scale as Category 3 or higher[3]. The greater the wind speed, the greater the sand-carrying capacity. Particles with a size of less than 20 microns[4] are the first to be transported by suspension, whereas particles with a size more than 500 microns move by reptation or creep. Saltation accounts for 80 per cent of the migration of sand with sand particles ranging in size from 70-1000μm move by a hop or bouncing action across the ground, causing other sand grains to hop along in the wind when they are struck by a falling grain (Figure 10; Chevron 2012, Lancaster 2009). As a result of the physics of the sand-grain movement the windward slopes have an angle of 10-15° which is lower than the slip face which has an angle of 30-34° (Figure 11).

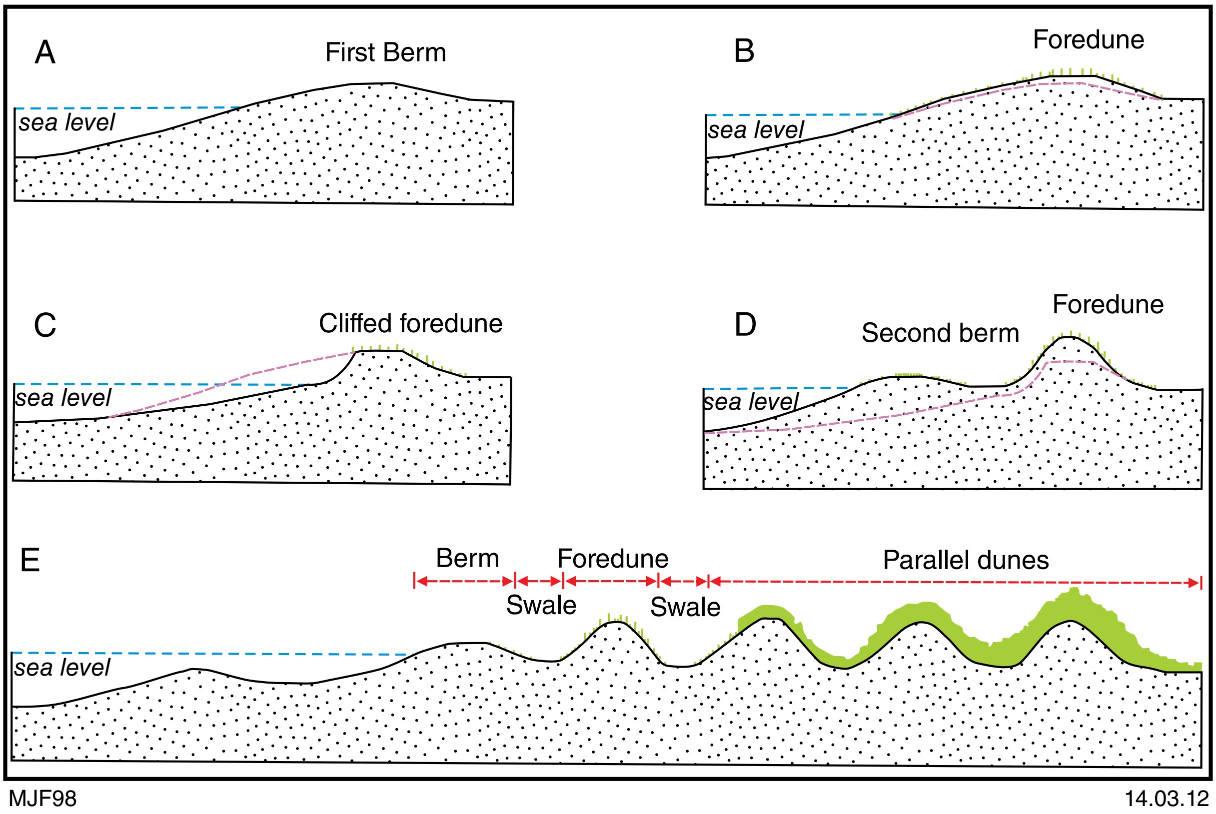



**Figure 8. Development of parallel dune ridges (after Bird 1984)**

[3] The Beaufort Wind Scale describes the wind velocity and the system was derived from a perspective of classifying oceanic or marine wind conditions. The Scale starts at 0 (0km/h) and ends at 12 (>118km/h). Wind with a Beaufort Scale 3 has a velocity of 12-19km/h (BOM, 2011).

[4] One micron (abbreviated μm) is 1/1000th of a millimetre. Therefore, 20μm is 1/50th of a millimetre and 500μm is half of a millimetre.

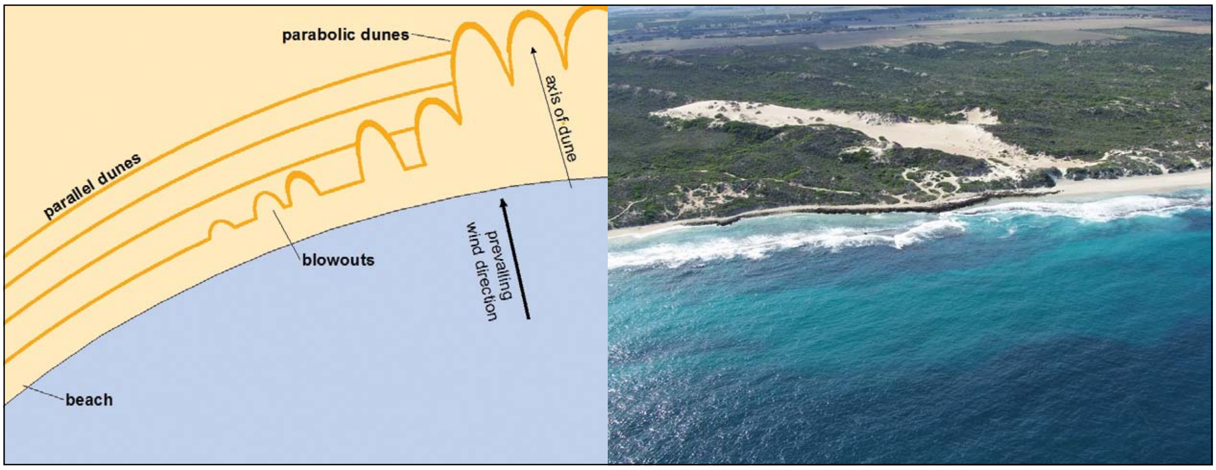



Figure 9. Blowouts in Western Australia (DERM, not dated) and an example of the development of a relatively new blowout south of Dongara.

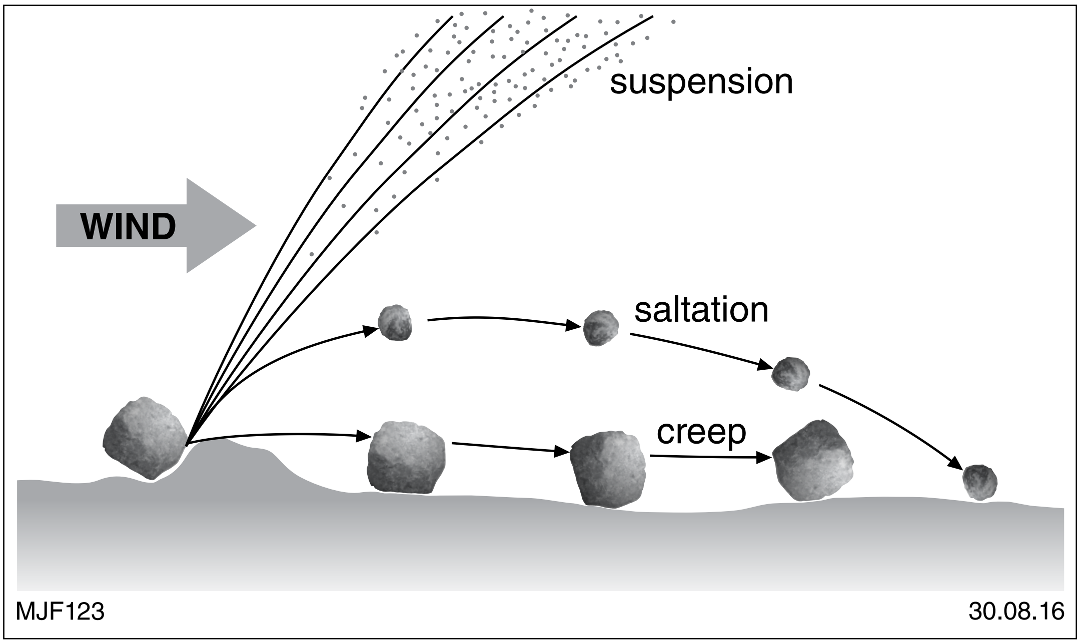



Figure 10. Forms of sand grain movement (NASA 2011)

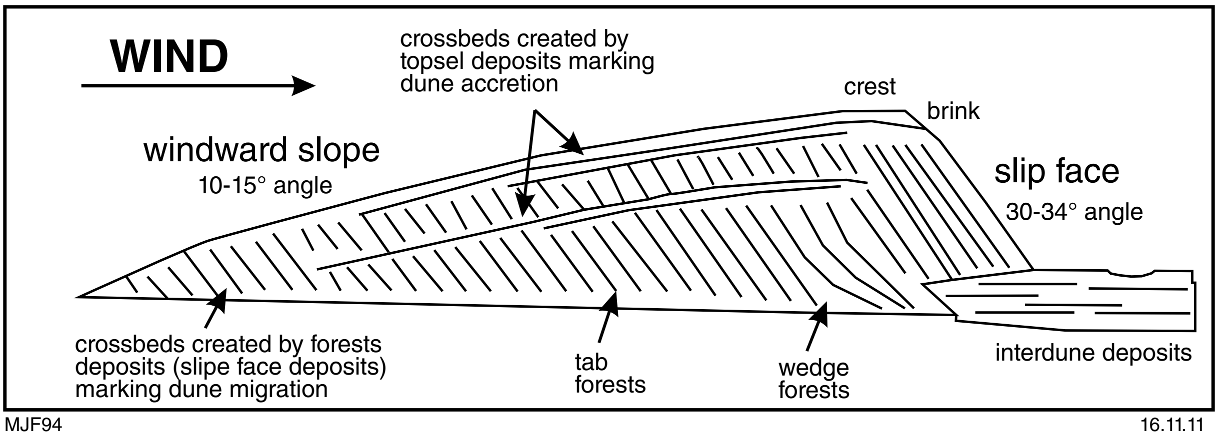



Figure 11. Morphology of a dune. Note orientation of internal bedding (Chevron 2011)

# Migration of dunes in Western Australia

## Migration direction and velocity and areas of mobile sand dunes

To measure the migration rate of the dunes from 1960 to 2010, each dune nose was identified and used as the basis for measurement. Due to the complex dune morphology within the study area, blowouts on the nose or limb of the dunes can occur and migrate at a different rate than the rest of the dune or of an adjacent lobe of the dune. In order to provide a reasonable measurement of the migration rate, the location of the nose was determined at several points across the front of the dune and these determinations used to measure the migration rate.

The dune speeds were determined in three discrete periods and an overall analysis conducted for the whole 50-year period. The periods are:

- Period 1 1960 to 1982
- Period 2 1982 to 2001–04
- Period 3 2001–02 to 2010

However, because imagery was not consistently available for all the area for each time, there were gaps in the data and the Period 2-Period 3 break was not consistent between all dunes. Details of the measured movement direction and speed are contained in Table 2. The migration direction and velocity is influenced by a range of factors, including wind direction, size, shape and type of the dune, vegetation cover, rainfall, temperature and the morphology and nature of the nearby coastline and ocean currents. Figure 12 shows the generalised outline of the dunes as drawn from the first and last dates images are available.

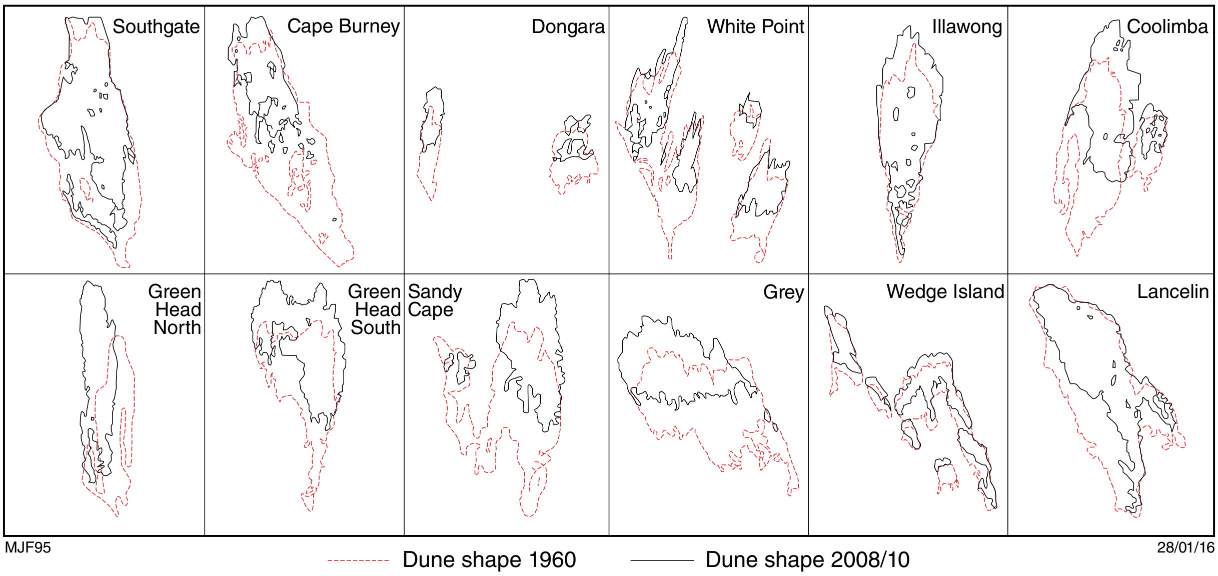



**Figure 12. Limesand dunes showing overall movement and change of shape from 1960 to 2010**

The mean direction of all the sand dunes is towards the north although there are detailed variations from this general trend (Figure 13).

Dune areas were measured at up to seven discrete times. Table 3 shows the actual areas and the changes in the areas with time and Figure 14 and Figure 15 show graphically the measured areas for each dune for each measurement with the two graphs showing different scales to illustrate the dune sizes for convenience. Note that a few data values are omitted through not having complete imagery or through changes in nomenclature because dunes split apart. In 1960 the biggest dune in the study area was Wedge Island with a total area of 1997ha. During Period 1 this dune split into Wedge Island South and Wedge Island East. Wedge Island East is still the biggest dune in the study area with a total area now of 1005ha. Lancelin, the second-largest in 1960 at 1068ha, has decreased during the study period to 674ha, a decrease of 37 per cent. The smallest dune in size is Dongara East with 13ha in the year 2010. The average areas for each of the three periods for all dunes measured are shown graphically in Appendix B.

During the past 50 years only two dunes have increased in size. Green Head South has increased slightly by 3 per cent and now has a total area of 174ha and Illawong increased by 11 per cent per cent to 111ha.

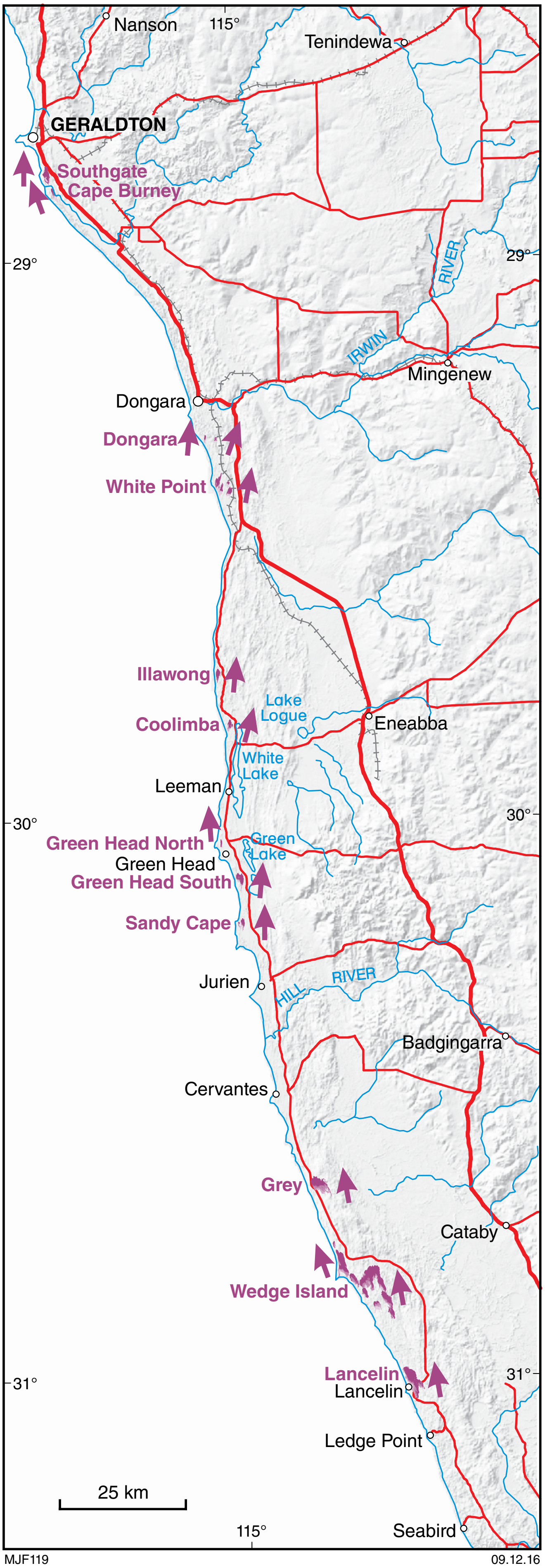



**Figure 13. Mid West coastal dunes showing average direction of dune migration 1960–2010. Note subtle variations of trends**

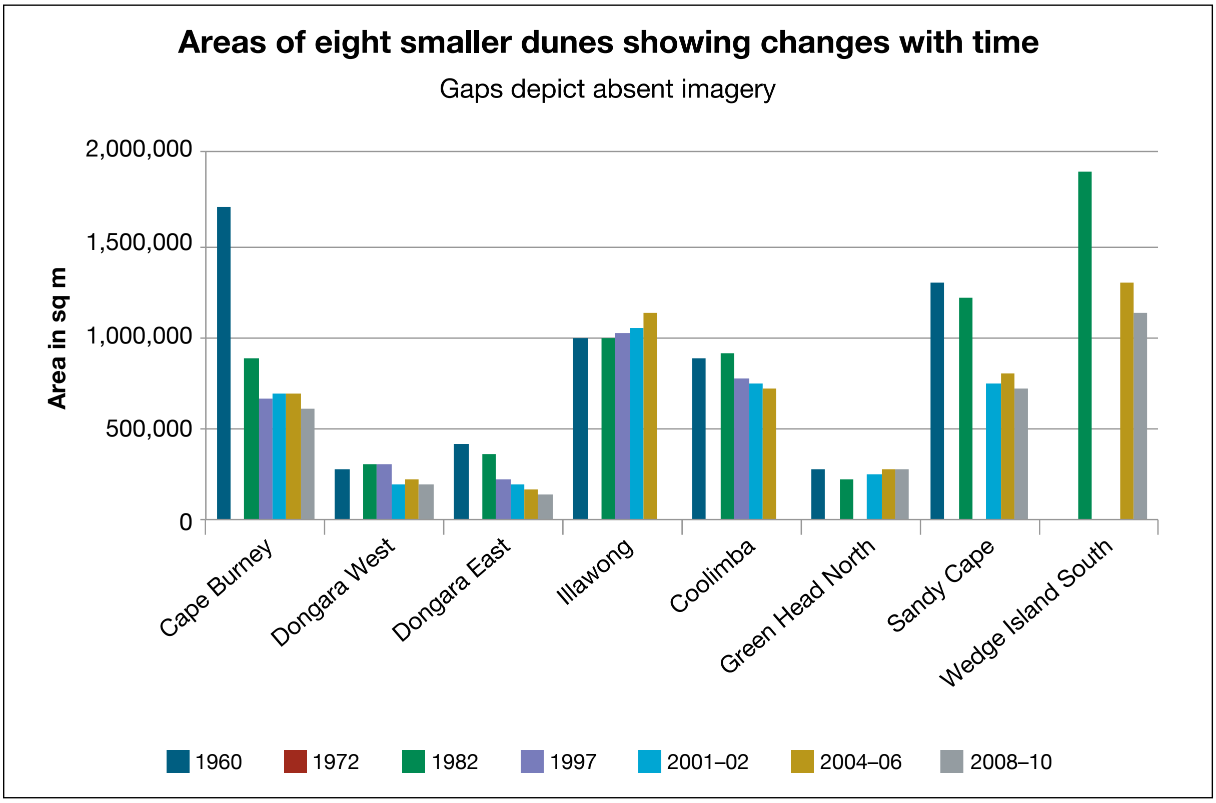



Figure 14. Areas of smaller dunes showing variations in time

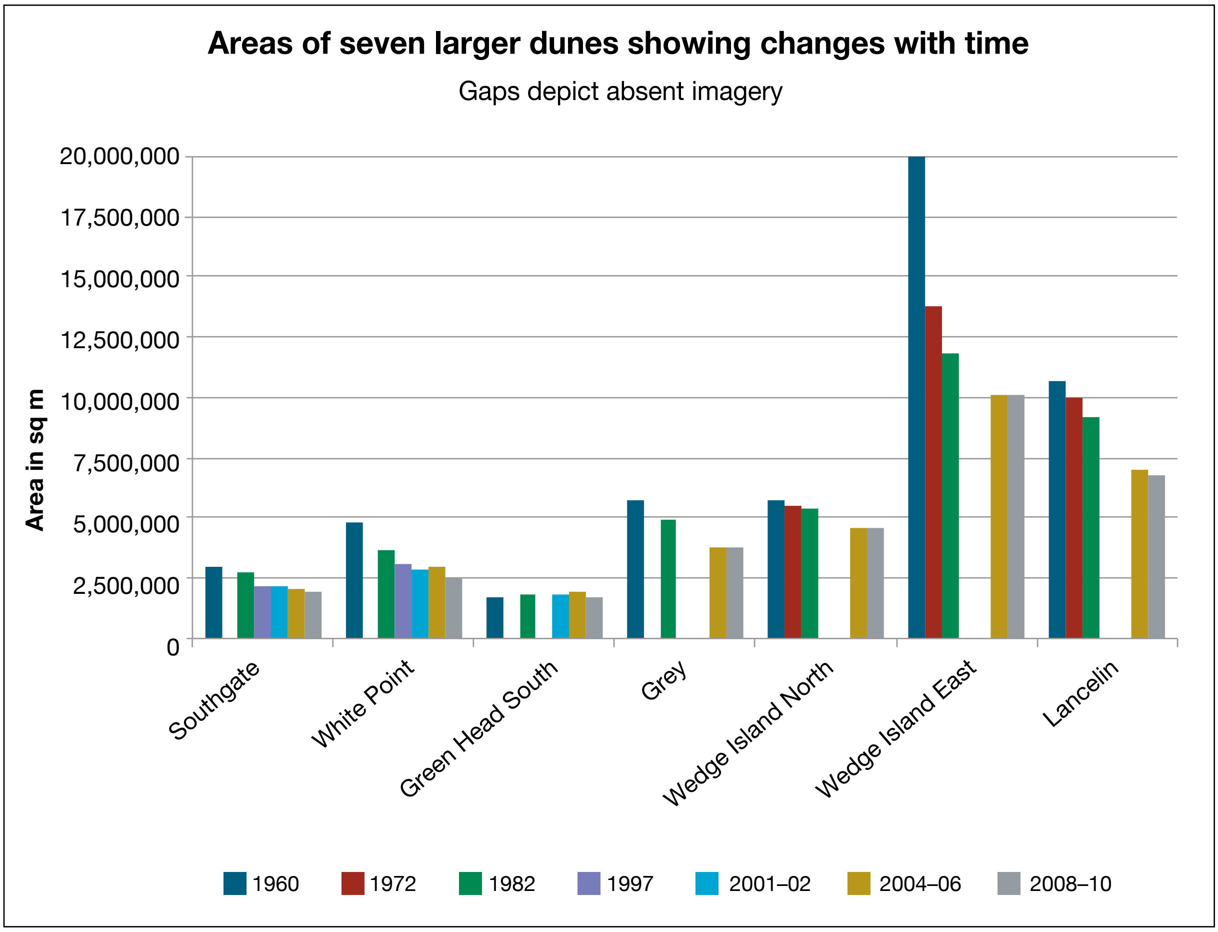



Figure 15. Areas of larger dunes showing changes with time

Table 2. Migration rate and migration direction of dunes.

| DUNE | MIGRATION RATE (M YEAR$^{-1}$) | | | MIGRATION OVERALL | |
|---|---|---|---|---|---|
| | Period 1 | Period 2 | Period 3 | Distance | Direction[5] |
| | 1960 – 1982 | 1982 – 2001/04 | 2001/04 – 2010 | (1960 – 2010) | |
| **Southgate** | | | | | |
| Migration in m | 155.6 | 70.2 | 114.4 | 340.2 | 0 |
| Migration rate m/year | 8.8 | 3.6 | 12.7 | 6.8 | |
| **Cape Burney** | | | | | |
| Migration in m | 64.0 | 118.7 | 91.0 | 273.7 | 340 |
| Migration rate m/year | 3.5 | 6.2 | 10.1 | 5.4 | |
| **Dongara West** | | | | | |
| Migration in m | 193.6 | 120.9 | 72.2 | 386.7 | 005 |
| Migration rate m/year | 8.8 | 6.3 | 8.0 | 7.7 | |
| **Dongara East** | | | | | |
| Migration in m | 99.25 | 89.5 | 20.2 | 209.0 | 020 |
| Migration rate m/year | 4.5 | 4.7 | 2.2 | 4.1 | |
| **White Point** | | | | | |
| Migration in m | 241 | 173.2 | 182.6 | 596.8 | 010 |
| Migration rate m/year | 10.9 | 9.1 | 20.2 | 11.9 | |
| **Illawong** | | | | | |
| Migration in m | 132.8 | 182.0 | 121.7 | 436.5 | 005 |
| Migration rate m/year | 6.0 | 9.1 | 30.4 | 9.4 | |
| **Coolimba** | | | | | |
| Migration in m | 164.6 | 166.9 | 25.7 | 357.2 | 015 |
| Migration rate m/year | 7.4 | 8.3 | 6.4 | 7.7 | |
| **Green Head North** | | | | | |
| Migration in m | 154.4 | 131.9 | 142.0 | 428.3 | 330 |
| Migration rate m/year | 7.0 | 6.5 | 17.7 | 8.5 | |
| **Green Head South** | | | | | |
| Migration in m | 351.8 | 151.9 | 124.3 | 628.0 | 005 |
| Migration rate m/year | 15.9 | 7.5 | 15.5 | 12.5 | |
| **Sandy Cape** | | | | | |
| Migration in m | 220.1 | 162.4 | 182.7 | 565.2 | 000 |
| Migration rate m/year | 10.0 | 8.1 | 22.8 | 11.3 | |
| **Grey** | | | | | |
| Migration in m | 235.6 | 448.6 | 71.9 | 756.1 | 350 |
| Migration rate m/year | 10.7 | 20.3 | 17.9 | 15.7 | |
| **Wedge Island North** | | | | | |
| Migration in m | 367.7 | 285.7 | 108.3 | 761.7 | 340 |
| Migration rate m/year | 16.7 | 12.9 | 27 | 15.8 | |
| **Wedge Island South** | | | | | |
| Migration in m | 222.0 | 215.3 | 75.8 | 513.3 | 340 |
| Migration rate m/year | 10.0 | 9.7 | 18.9 | 10.6 | |
| **Wedge Island East** | | | | | |
| Migration in m | 243.4 | 250.6 | 44.5 | 538.5 | 350 |
| Migration rate m/year | 11.0 | 11.3 | 11.1 | 11.2 | |
| **Lancelin** | | | | | |
| Migration in m | 835.1 | 237.3 | 24.7 | 1,097.1 | |
| Migration rate m/year | 37.9 | 10.7 | 6.1 | 22.8 | |
| **Mean migration rate** m/year | 9.23 | 8.95 | 15.13 | 10.76 | |

[5] Directions are bearings measured from true north in a clockwise direction

Table 3. Area and change in area of each dune[6].

| AREAS (M²) MEASURED BETWEEN 1960 AND 2010 | | | | | | | |
|---|---|---|---|---|---|---|---|
| DUNE | Areas (m²) | | | | | | |
| | 1960 | 1972 | 1982 | 1997 | 2001–02 | 2004/06 | 2008/10 |
| Southgate | 2,962,296 | | 2,693,939 | 2,113,919 | 2,153,982 | 2,018,804 | 1,937,807 |
| Cape Burney | 1,706,223 | | 870,156 | 659,727 | 676,457 | 692,181 | 600,049 |
| Dongara West | 265,405 | | 311,594 | 309,640 | 192,019 | 207,411 | 202,239 |
| Dongara East | 413,258 | | 345,394 | 217,230 | 180,506 | 166,126 | 137,087 |
| White Point | 4,831,483 | | 3,673,269 | 3,087,301 | 2,875,786 | 2,926,648 | 2,548,702 |
| Illawong | 999,645 | | 986,137 | 1,026,197 | 1,058,206 | 1,119,343 | |
| Coolimba | 888,560 | | 914,837 | 780,540 | 731,366 | 714,217 | |
| Green Head North | 288,006 | | 211,301 | | 239,268 | 284,975 | 286,532 |
| Green Head South | 1,688,424 | | 1,840,433 | | 1,822,274 | 1,913,820 | 1,743,305 |
| Sandy Cape | 1,289,965 | | 1,212,357 | | 746,635 | 805,077 | 714,878 |
| Grey | 5,770,899 | | 4,898,975 | | | 3,791,556 | 3,783,873 |
| Wedge Island North | 5,786,110 | 5,548,187 | 5,352,312 | | | 4,596,679 | 4,632,569 |
| Wedge Island South | 19,976,020 | 13,745,544 | 1,903,494 | | | 1,283,903 | 1,132,415 |
| Wedge Island East | | | 11,841,847 | | | 10,155,176 | 10,058,170 |
| Lancelin | 10,680,570 | 9,994,183 | 9,140,837 | | | 6,962,595 | 6,744,495 |

| CHANGE IN AREA (M²) FROM 1960 TO 2010 | | | | |
|---|---|---|---|---|
| DUNE | Change in areas for periods (m²) | | | OVERALL M² |
| | 1960 – 1982 | 1982 – 2004/06 | 2004/06 – 2008/10 | |
| Southgate | -268,357 | -675,135 | -80,997 | -1,024,489 |
| Cape Burney | -836,067 | -177,975 | -92,132 | -1,106,174 |
| Dongara West | 46,189 | -104,183 | -5,172 | -63,166 |
| Dongara East | -67,864 | -179,268 | -29,039 | -276,171 |
| White Point | -1,158,214 | -746,621 | -377,946 | -2,282,781 |
| Illawong | -13,508 | 133,206 | | 119,698 |
| Coolimba | 26,277 | -200,620 | | -174,343 |
| Green Head North | -76,705 | 73,674 | 1,557 | -1,474 |
| Green Head South | 152,009 | -1,838,519 | 1,741,391 | 54,881 |
| Sandy Cape | -57,608 | -407,280 | -90,199 | -555,087 |
| Grey | -871,924 | -1,107,419 | -7,683 | -1,987,026 |
| Wedge Island North | -433,798 | -755,633 | 35,890 | -1,153,541 |
| Wedge Island South | | -619,591 | -151,488 | -771,079 |
| Wedge Island East | -8,134,173 | -1,686,671 | -97,006 | -9,917,850 |
| Lancelin | -1,539,733 | -2,178,242 | -218,100 | -3,936,075 |

[6] Note that dunes Wedge Island East and Wedge Island South split apart between 1972 and 1982

In comparison, all other dunes in the study area have decreased in size in the past 50 years. Those of most significance were White Point dune field which decreased from 308ha in 1960 to 175ha in 1982. The other significant decrease occurred at the Lancelin dune from 1982 to 2004 – a decline of 200ha.

There is a correlation between the size of the dune and the migration rate. Fundamentally, the bigger the dune is, the faster it is migrating. For example Dongara East and West have the smallest areas and the lowest mean migration rate per year, whereas the bigger dunes of Wedge Island North and Grey had higher migration rates per year. Figure 16 graphically shows the relationship between size in 2010 and the average speed for the period 1960–2010. However, Wedge Island East is anomalous in that while it is the largest dune at 1006ha in 2010, for the 50-year period its average speed was a relatively low 11.2m/year. Examination of the situation of Wedge Island East dune shows that it is anomalous from a height perspective. Most of the dunes in the study did not climb upslope much, with Grey and Wedge Island East being the exceptions. Appendix D shows graphically the anomalous height situation of Wedge Island East dune. This also is the largest sand sheet on the coast and that fact may have had some influence on the speed. Three Wedge Island dunes were mapped for this exercise. However there are seven or eight individual dunes that extend over distances of 15km north-south and 5km east-west that could be grouped genetically because they appear on airphotos as having a common origin from the same beaches. This is a complex dune area and it is inferred that this complexity of forms may also be part of the reason why Wedge Island East dune has an anomalous speed/size relationship. As a consequence of this dune's speed being an outlier, it was removed from the graph (Figure 16) because of its very large effect on the relationship line for all the other dunes. If Wedge Island East was to conform to the relationship as shown by the correlation line, it would have had an average speed over the 50 years of three times its measured speed.

In Figure 16 the trend line implies that for the 50-year period the dunes had a rate equivalent to one metre a year for each 50ha of bare dune sand. However, this value as noted above, only applies to time frames of the order of 50 years and the relationship between area and speed should not be applied to shorter periods in attempts to project future movements of the dunes.

Figure 17 shows diagrammatically the dune speeds in each of the three individual periods plotted against the area showing the much larger scatter of data points and the inconsistency between area and speed within each of the three periods. It is particularly noted that there is greater scatter in Period 3 as most dunes increased in speed. This suggests that local variations in the factors controlling the dune speed can have a dominating influence on short-term behaviours of the dunes, but that for five decade averages these local controls are less important.

By comparing the 1910 Campbell map (op cit) of dunes (Figure 3) with the more recent images, it was noted that the dune migration rate between 1910 and 1960 was twice as rapid as the migration rate between 1960 and 2008–10. Possible causes of the faster historic migration could be a different climate, higher level of human activity or an inaccuracy of the 1910 Campbell map. While Campbell focused on the importance of the outline and the form of the dunes, the location of the dunes in the 1910 map is considered not to be accurate enough for the present higher precision analysis.

Examination of the regional dune pattern clearly shows the trailing arms of the parabolic dunes as they passed onwards (Figure 18). Once stablised, the limesand rapidly (geologically speaking) becomes cemented to form limestone, preserving the traces of the migration. Based on these remnant traces of the trailing arms, some of the dunes have migrated considerable distances. Because of successive generations of dunes blowing over older dunes, in many cases the source beach of the most inland dunes is not readily apparent. However, for example, there are good indications that dune remnants appearing to emanate from the bay adjacent to Wedge Island had progressed some 21km before finally stopping. Likewise older dunes emanating from the bay south of Cervantes migrated 15km before totally stabilising. Near Dongara, the distance travelled appears to be in the order of up to 10km while north of Dongara it decreases to 2km. As noted above, it is inferred that this regional change relates to decreases in the supply of sediment onto beaches to the north.

In general directional terms, south of Jurien Bay (Grey to Lancelin) the dunes are moving north-northwesterly, parallel to the coastline. In comparison the limesand dunes north of Jurien Bay are moving northwards to north-northeasterly (Dongara to Sandy Cape). However, north of Dongara the trend reverts to west of north at Southgate and Cape Burney. The migration directions of each dune range from 330° to 020° (north-northwesterly to north-northeasterly). The dunes migrate dominantly in parabolic form and leave tails behind. The tails usually have depleted levels of vegetation, even a long time after stabilisation. These poorly vegetated dune ridges or tails show clearly as white traces on airphoto and satellite images and stand out on images showing enhanced relief (Figure 18).

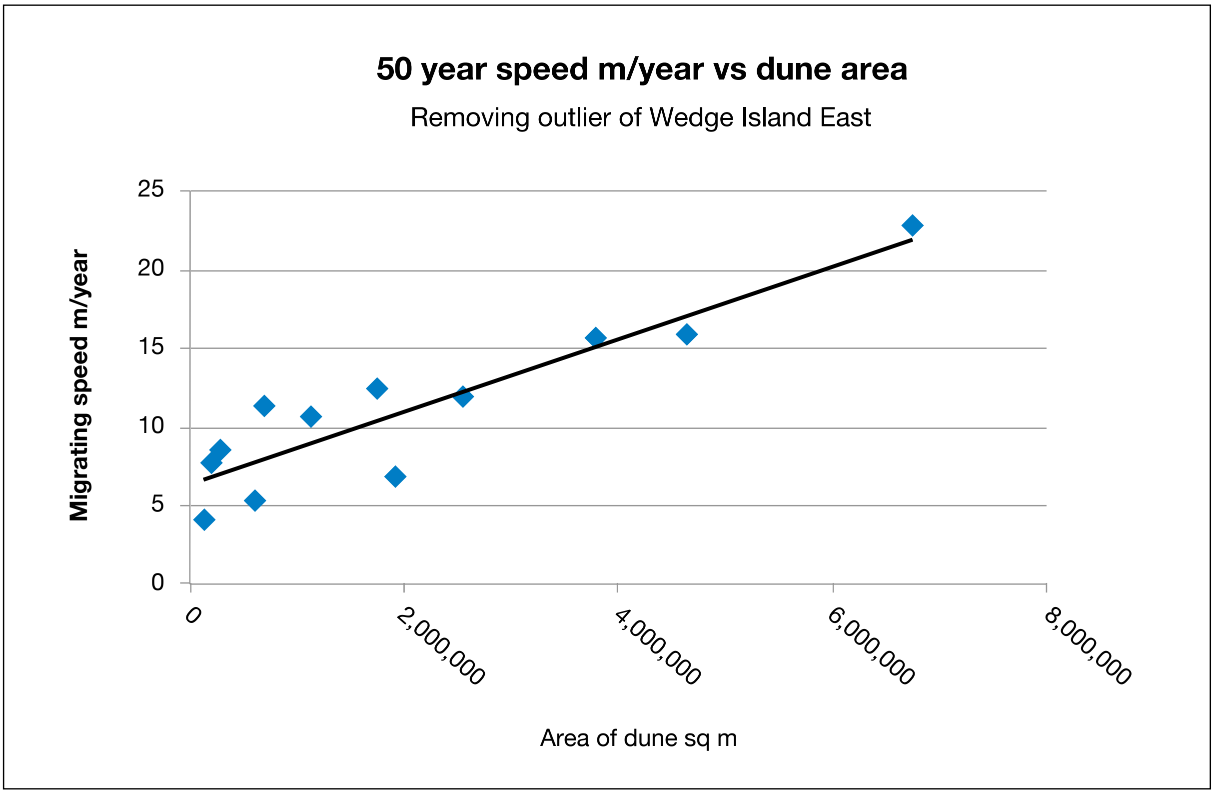



Figure 16. 50-year average speed of dunes showing correlation line between speed and size.
Note that Wedge Island East dune is deleted from the graph as being an outlier to the data.

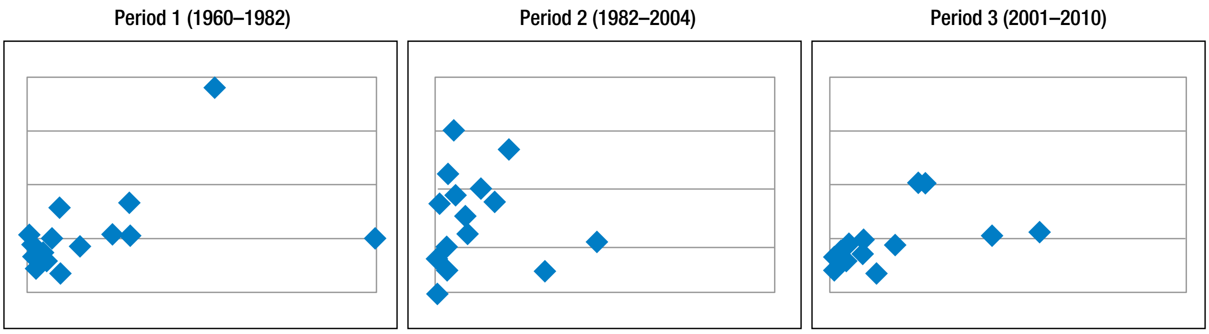



Figure 17. Speed of dunes plotted against dune area in Periods 1, 2 and 3 respectively
Note: The three graphs have the same abscissa and ordinate scales to permit direct comparison although the axis data is omitted for simplicity of presentation. While there is a general relationship between size and speed for each of the shorter periods, the correlation is far inferior to the correlation over a 50-year period as in Figure 16.

The dune migration rate was measured by calculating the distance from nose to nose and did not take into account the nature of the movement within the rest of the dune, with the exception of the Lancelin dune. Due to movement only occurring on the west side of the Lancelin dune the trailing arms were also measured to determine the migration rate.

As the Lancelin dune is not specifically moving in any particular direction, because it is actually decreasing in size, it was therefore excluded from the analysis of the overall migration velocity.

There is a large range in the speed of the various dunes with the slowest at 2.2m/year and the highest at 37.9m/year (Table 2). The Illawong dune had a large acceleration from 6.0m/year in Period 1 and 9.1m/year in Period 2 up to the unusually fast 30.4m/year in Period 3. At the opposite extreme, Dongara East increased slightly from 4.5m/year in Period 1 to 4.7m/year in Period 2 but then slowed to half at 2.2m/year in Period 3. White Point and Sandy Cape dunes markedly accelerated in Period 3. The biggest change was Lancelin that slowed from an extremely fast 37.9m/year to 10.7m/year from Period 1 to Period 2. The dunes Grey and Wedge Island North, both located in the south of the study area, have the highest mean migration rate within the period 1960–2010, with 15.7m/year for Grey and 15.8m/year for Wedge Island North. The lowest mean migration rate has taken place at the dune Dongara East with only 4.1m/year for the whole 50 years.

As an overall statement, the migration rate decreased slightly in the second period (1982–2001) but then increased again in the Period 3, when most of the dunes became highly active and with the migration rate reaching its highest. This is shown by the simple average speeds of all the dunes, at 11.3m/year in Period 1, decreasing to 9.5m/year in Period 2 and then rising to 15.1m/year in Period 3, meaning that the average speed in Period 3 was 34 per cent above that in Period 1. There were exceptions with the Dongara East and Coolimba dunes where the migration rate actually decreased in the past 50 years. Overall, there is considerable inconsistency in the variations of rate depending on the periods and the particular dunes and it is concluded that extrapolation of the present migration rates into the future should be considered only with a significant variation likely.

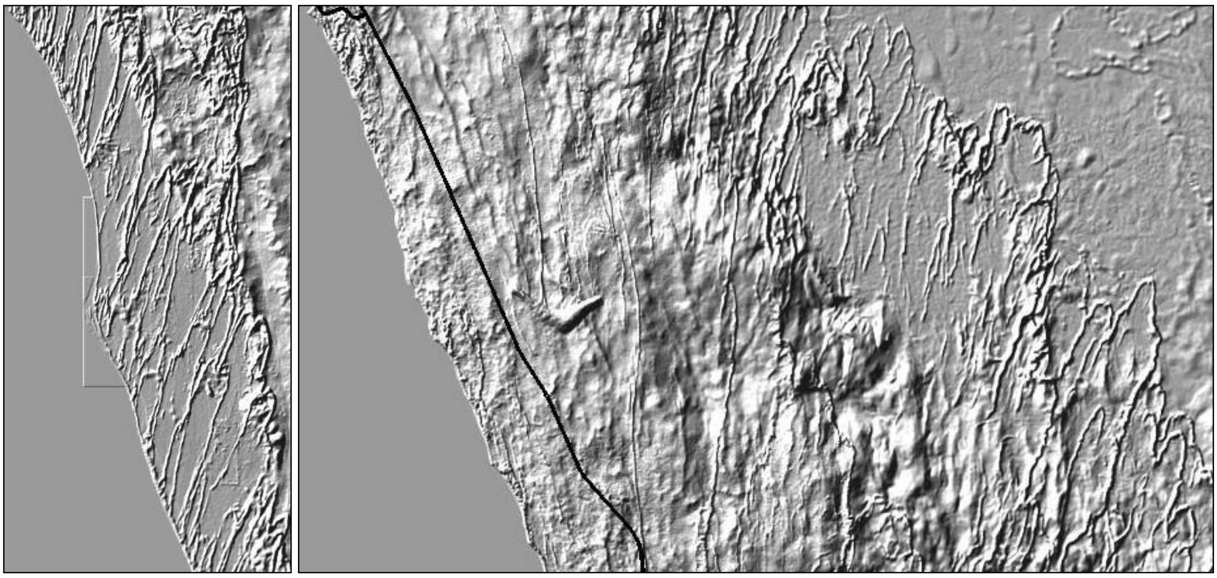


**Figure 18. Relict dunes showing the stabilised lateral arms and the parabolic shape reflecting the stabilised head of the former dune. Left-hand image shows White Point and the right-hand is Wedge Island. Images compiled by ehancing the digital relief model and illuminating with strong, low-level source on west (left) horizon. The sharp lines are the stabilised lateral tails and the heads of the parabolic dunes. The left-hand image is 17km north to south (top to bottom) and the right-hand image is 13km north to south.**

# Migration influenced by climate

To ascertain whether the migration rate of the dunes is influenced by climate, various rainfall, temperature and wind, data were analysed for the towns of Geraldton, Jurien Bay and Lancelin.

- Geraldton (Latitude: 28.77°S · Longitude: 114.61°E) situated in the north of the study area with an elevation of 9m.
- Jurien Bay (Latitude: 30.31°S · Longitude: 115.03°E) is sheltered by a string of islands and reefs and has an elevation of 2m.
- Lancelin (Latitude: 31.02°S · Longitude: 115.33°E) has an elevation of 4m and is located in the south of the study area

## Wind influence

Diurnal change causes the sun, during daytime, to create higher temperatures over land than over the sea, causing the inland air to rise and creating a lower pressure system over the land's surface. As the sea surface temperature increases slower than on the land, it results in a higher air pressure over the ocean. The different pressures create a sea breeze that blows inland from west to the east along this coast and speeds of 25-30km/h are not uncommon for these sea breezes. By contrast, a land breeze is created at night when the land cools more than the water because water, having a higher specific heat capacity, stores the heat energy longer than the land. The resultant air-pressure differential results in the higher-pressure land air pushing the lower-pressure sea air upwards and creating a land breeze. Typically, land breezes are of a lower velocity than the sea breezes due to a lower temperature contrast between the two surfaces from day to night (Figure 19).

The wind direction in the study area has a seasonal as well as a diurnal pattern. During the summer months of November to February strong winds are southerly. In comparison during the winter months there is a dominance of oscillating easterly and westerly winds (BoM 2011).

The west coast sea breeze in summer in Western Australia is controlled by two forces. Pattiaratchi et al (1997) noted that in summer a low pressure trough forms parallel to the coast due to the intense heating of the air across the continent and this leads to inflow of air from the

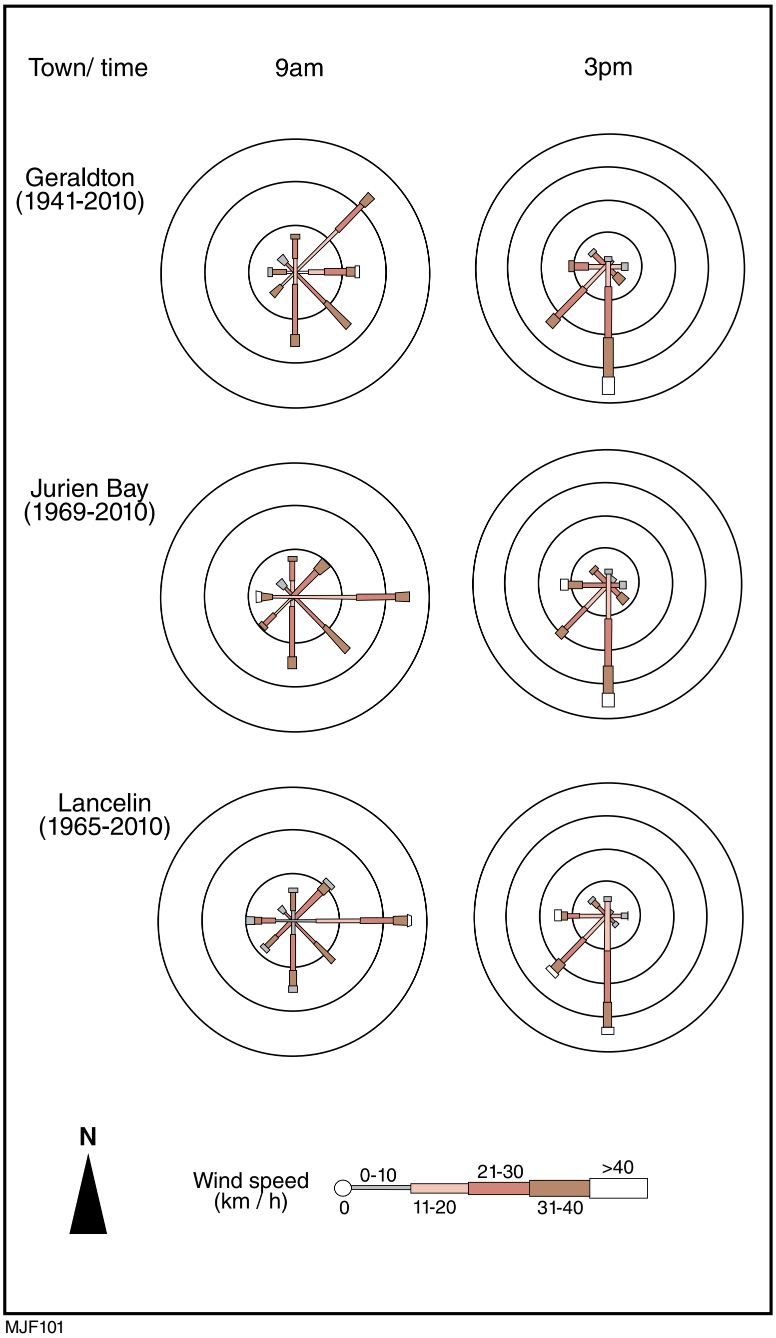



Figure 19. Annual wind rosettes for Dongara, Jurien Bay and Lancelin (BOM 2011).

northeast. However, there is also a synoptic development caused by a very large-scale pressure gradient that generates a southwest air movement potential. The combination of the general synoptic weather pattern and the west coast trough with additional influences from diurnal variations and the Coriolis[7] force generate a dominant southerly air movement. This combination of the potential blowing directions results in one of the strongest southerly sea breeze systems in the world with mean wind velocities of 36km/h but with a direction nearly parallel to the coast.

In winter, there is dominance by an easterly-moving high-pressure anticyclone belt through the Mid West coastal region. Low pressure cells and frontal systems trail each anticyclone with strong winds initially from the northwest and then from the southwest as they recede to the east with the latter causing rainfall and storm events (Pattiaratchi et al. 1997). In summer, the west coast trough becomes established after anticyclones have passed and may remain in place or even migrate slowly to the west offshore for several days, strengthening with time. This draws in low-humidity, hot air from the interior of the continent leading to marked drying off of the region's soils as well as stressing vegetation and contributing to decreased foliage density on the sand dunes.

Figure 19 shows average wind rosettes for varying periods for three major settlements. Winter winds have strongly contrasting directions between mornings and afternoons. In the morning the winds blow from the east or northeast for between 10 per cent and 30 per cent of the time and, in the afternoon, from the south for between 15 per cent and 22 per cent. Lesser components are a northeasterly wind for between 10 per cent and 15 per cent of the time, particularly in the northern part of the area. Therefore the wind direction in winter is highly variable and consequently can be regarded as having a fairly balanced potential to move sand, especially in the afternoon.

During summer by 9am, between 25 per cent and 35 per cent of the wind is southerly whereas between 17 per cent and 23 per cent is from the east to southeast with main wind velocities ranging between 20 and 30km/h. By 3pm, very strong southerly winds develop with 55-62 per cent of all winds blowing from this direction reaching velocities of over 40km/h, with southwesterly winds accounting for between 25 per cent and 30 per cent of the wind direction and having wind velocities of between 20km/h and 30km/h (BoM 2011).

The shore-parallel sea breeze in Western Australia is an unusual phenomenon. During summer there are few westerly morning winds or easterly afternoon winds because the wind blows parallel to the shoreline. In addition, there are slight changes in the orientation of the dune direction and hence average wind direction during the periods of mobility. The consequence of this is strong south-southeast winds in the areas south of Jurien Bay, south or south-southwest winds in the areas from Jurien Bay to Dongara and returning progressively to south and then south-southeast winds to the north of Dongara. However, the strong summer shoreline-parallel sea breeze results in all sand dunes migrating subparallel to oblique to the shoreline.

Yao et al. (2007) identified three prime factors that can create the optimal conditions for high rates of sand migration:

- Dry weather and substrate
- Strong prevailing winds
- None to minimal vegetation coverage

In the study area the driest part of the year in summer occurs when the consistent afternoon sea breeze from the south is strongest. During these summer months the southerly wind velocities reach 40km/h for between 10 per cent and 15 per cent of the time. During this period the dryness of the substrate minimises vegetation density and foliage growth and in extreme periods causes deaths of plants which, coupled with the high wind velocities, ensures maximum sand migration potential occurs in this period. There may also be an influence from electrical storms starting bushfires that bare the sand and may lead to initiation of dune blowouts.

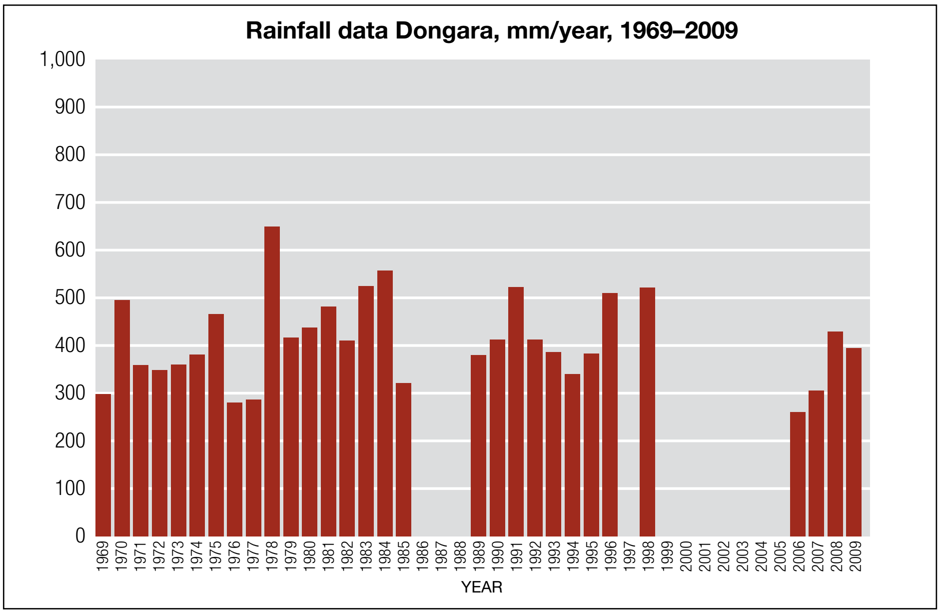
## Rainfall and temperature influence

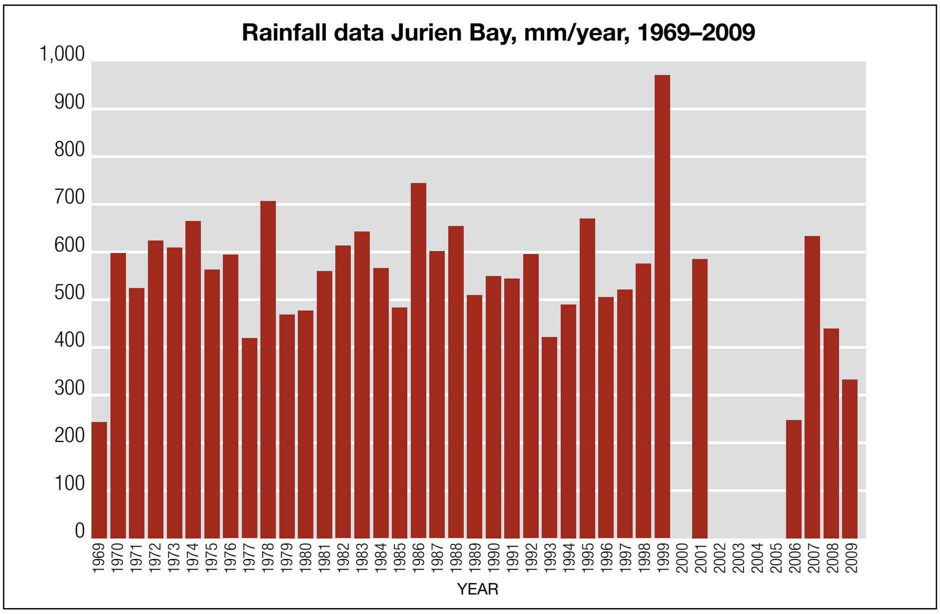
The annual rainfall increases from north to south through the study area. During the 40-year period 1969–2009 the mean rainfall figures for three major towns were:

- Dongara 386mm a year
- Jurien Bay 535mm a year
- Lancelin 623mm a year

Based on the three time periods of data from above (1960–82, 1982–2001 and 2001–10) the lowest rainfall data for Dongara and Jurien Bay occurred in the third period (Figure 20) which correlates with the highest dune migration rates.

[7] Coriolis force is the property derived from the rotation of the Earth that deflects the wind to the left in the southern hemisphere, thereby generating circular winds around pressure centres.



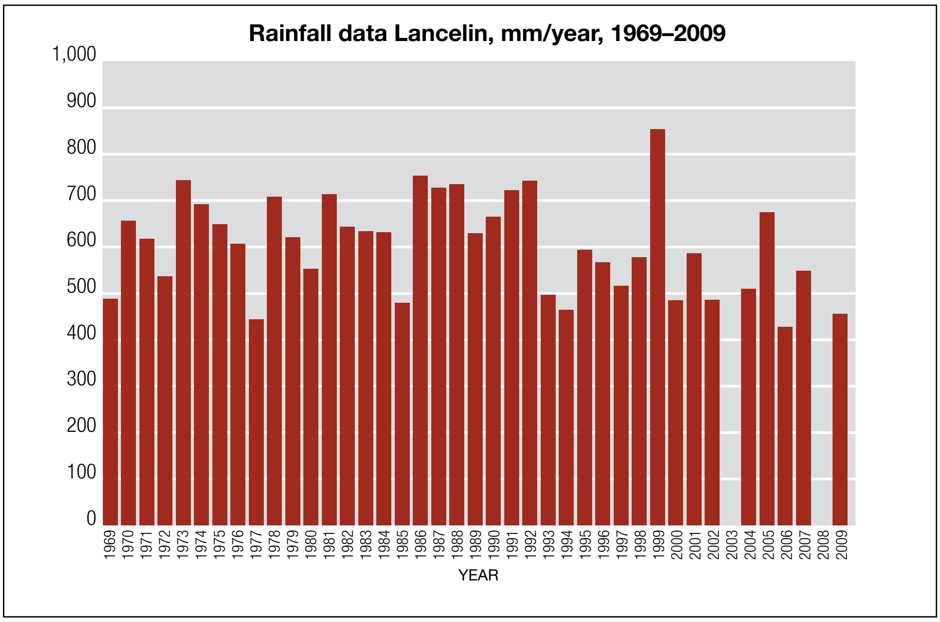




Figure 20. Rainfall data for Dongara, Jurien Bay and Lancelin between 1969 and 2009 (BOM 2011)

However, it is important to note that at Lancelin there was not a significant decrease in the annual rainfall during the third period and the migration rate was no greater than that of the second period.

The highest rainfall occurs in winter (June to July) and the lowest in summer (December to January). The significant anomaly in the year 1999 (Figure 20) was due to the La Niña effect. La Niña is a phenomenon caused by a cooler than normal sea surface temperature of the eastern Pacific Ocean which influences the weather in Australia, bringing rain and flooding, particularly in the eastern and northeastern parts of Australia (BoM 2005). This phenomenon impacted the study area from April to September 1999 (Figure 21) when the rainfall reached levels well above average.

An important consideration for this research is the impact of the El Niño effect on the west coast of Australia (Figure 22). El Niño is a phenomenon that occurs intermittently, in periods ranging from one to 26 years, and relates to a higher sea surface temperature in the central and eastern Pacific Ocean, which can influence climate worldwide. A strong El Niño causes drier than normal conditions over Australia (BoM 2005), particularly eastern and northern parts and although the effects can occur over Western Australia they tend to be weaker. Significant rainfall decreases were observed in the years 1977, 1994 and 2006 for Dongara, Jurien Bay and Lancelin (Figure 20). The year 2006 was especially dry with rainfalls of 428mm in Lancelin, 248mm in Jurien Bay and 260mm in Dongara. For all three towns it was one of the driest or the driest year in the 40-year period 1969 to 2009. That year also was unusually hot with Jurien Bay reporting a mean maximum temperature of 25.6°C and Dongara a mean maximum of 26.9°C respectively (compared with long-term averages of 24.9°C and 25.2°C). Lancelin's highest mean maximum temperature was 26°C in 1978 which coincides with the highest migration rate of the Lancelin dunes in the first period (1960–1982). For the majority of the other dunes, the highest migration rate occurred in the third period between the years 2001 and 2010. Within this third time period two El Niño events impacted the study area (BoM 2011). This helps to explain the higher dune migration rate, averaging 15.13m/year, occurring in Period 3.

Dune migration and the initiation of blowouts will be enhanced when the sand is driest and the vegetation cover is minimised. As noted above, this occurs in summer when the west coast trough has been drawing in dry, hot air from the interior of the continent and this wind has prevailed for several days. Anecdotal comments from residents living or working near mobile dunes supports this contention by having noted that a single due front may advance by one or several metres over a few days in summer, but then not migrate much for weeks or even for the rest of the year.

## Migration influenced by dune type

Coastal dunes form under different conditions from inland or desert dunes. Firstly coastal weather is more humid than in the desert and therefore more vegetation can grow. As such, coastal dunes are often isolated from each other by vegetated areas (Ronca, 2011). The formation of a dune type depends on the presence or absence of vegetation, its degree of coverage and the wind speed and directions. The majority of the dunes analysed in the study area can be classified as parabolic dunes, eg. Dongara West and Wedge Island South. However, the migration of parabolic dunes is poorly understood or analysed.

Essentially a parabolic dune is a blowout that commences in a part of a coastal parallel dune. With a parabolic dune, the dune crest (central blowout) advances rapidly but the limbs are held back by lower wind velocity, possibly caused by vegetation, thus lengthening the dune in a windward direction. However, changes in vegetation can destabilise the parabolic dune morphology and the shape changes (DERM, 2011). With the limbs becoming stabilised, the quantity of sand in the head of the dune progressively decreases. Ultimately too little sand is left and the head becomes stabilised and the dune migration ceases as shown by the relict dune traces in Figure 18.

The majority of the dunes studied have forms related to parabolic types, though a number have been modified from a clearly parabolic shape. The Southgate-Cape Burney dunes in the north and the Wedge Island East and Lancelin dunes in the south of the study area deviate most from the parabolic shape and are better considered as transgressive dune sheets. A transgressive dune sheet occurs specifically in areas with abundant sand supply, powerful onshore winds and winds that may seasonally vary in direction. They are commonly formed from parabolic dunes when the vegetation cover over the trailing arms is removed (Hesp 1990) or does not form a complete coverage, coupled with a copious supply of sand.

Older relict fixed dunes in the study area consist of limesand grains (calcium carbonate) which became cemented to form limestone. This process is called lithification and has been occurring and stabilising the limesand dunes since Pleistocene time (Bird 1984). These are now evident as relict dunes that are still visible from the air (Figure 18), but they are now covered with climax vegetation. The stabilised limbs left behind commonly retain little vegetation and show as semi-continuous slightly wavy white lineaments on airphoto or satellite images.

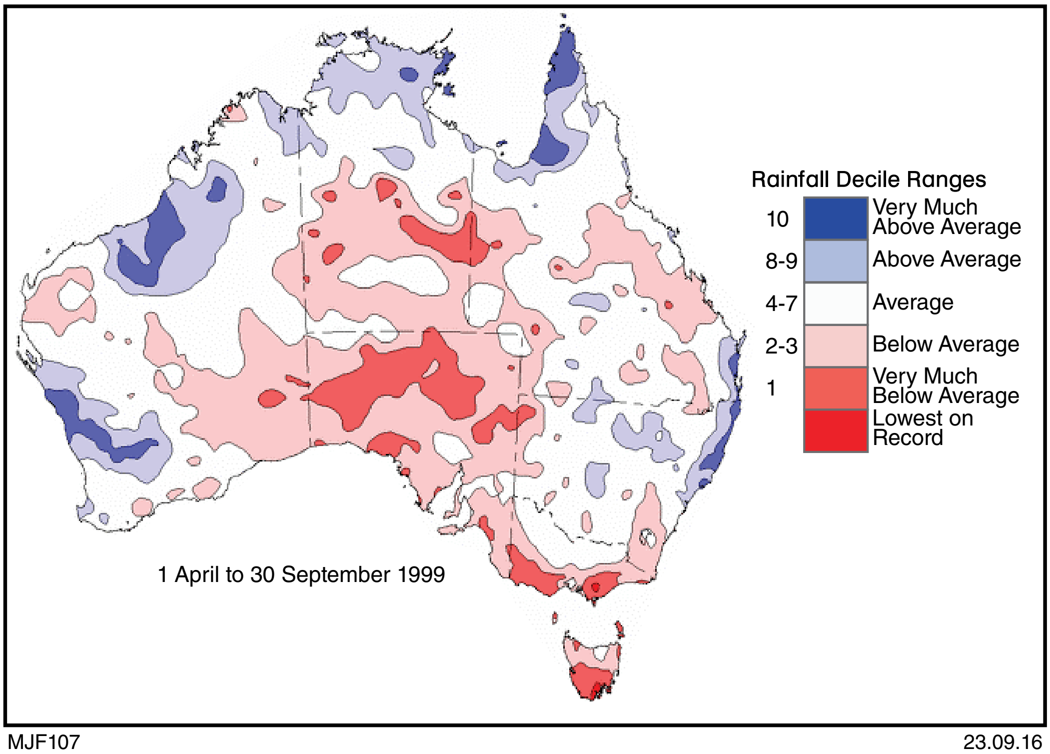



Figure 21. La Nina effect in 1999 (BoM 2011)

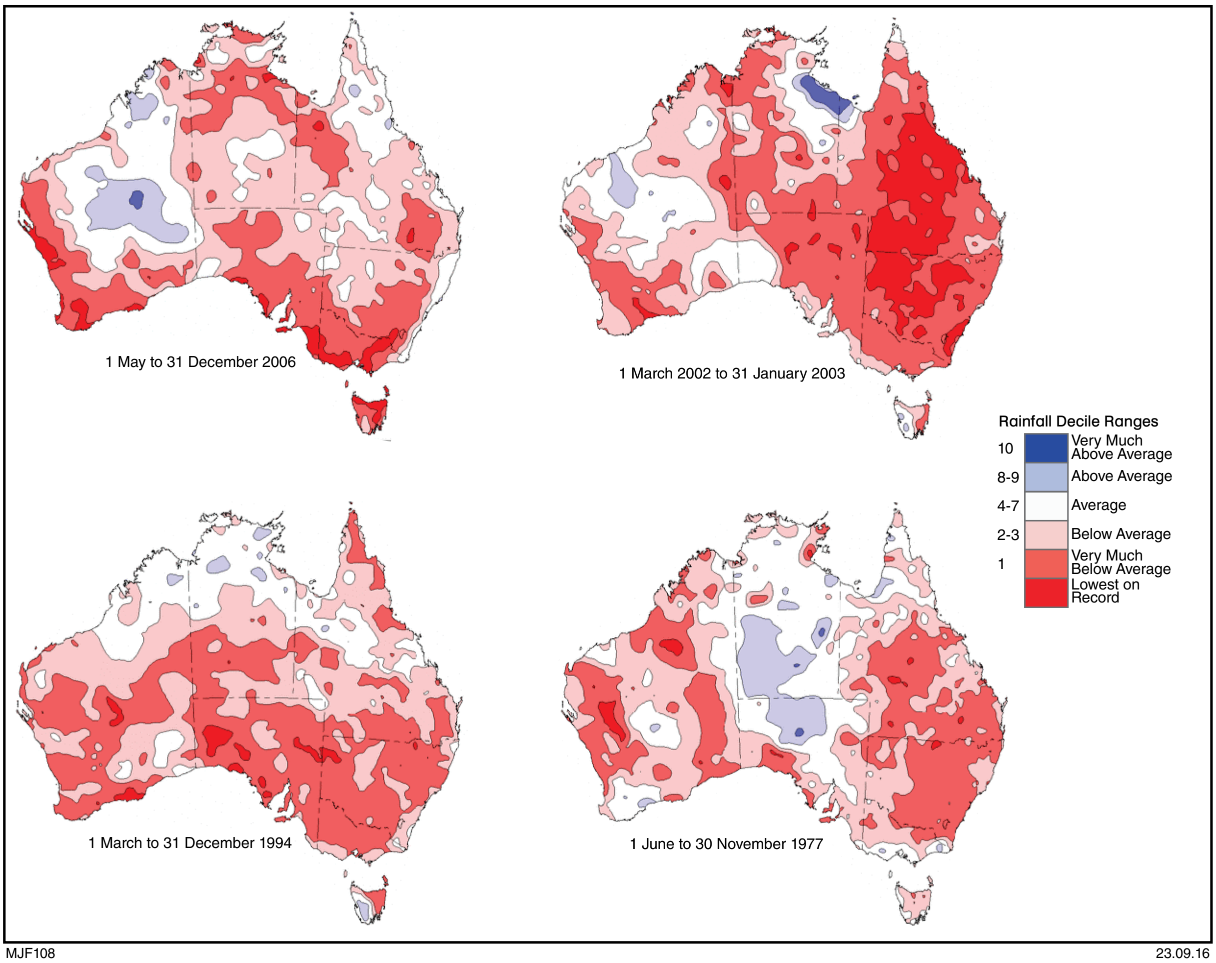



Figure 22. El Niño in the years 1977, 1994, 2002 and 2007 showing very low or lowest-on-record rainfall for the study area (BoM 2011).

## Migration influenced by offshore effects

A long, continuous limestone reef system occurs along the Mid West coast of Western Australia. This is located up to 10km west of the coast of the study area parallel to the coastline and extends over some 300km from near Jurien Bay to Cape Bouvard, south of Mandurah, and with sporadic, short reefs between Jurien Bay and Geraldton. The offshore reef development occurred originally when the feature was an onshore limesand dune at times of lower sea level. Following formation of the dune, the limesand became cemented to form the limestone. The presence of this reef system exerts a significant controlling influence on the sand deposition along the beaches.

Sand deposition on beaches is strongly controlled by the coastal morphology and in particular by the concept of littoral cells where sand is cycled onto the beach and then eroded off the beach in storm periods, while moving laterally along the beach. Each littoral cell functions as an isolated cell with sand not moving laterally from one cell to the adjacent cell or moving in restricted quantities, except in times of exacerbated activity through strong longshore movement or through extreme storm event (Bray et al, 1995; Finkl, 2004; Masselink and Pattiaratchi, 2000).

Sanderson and Elliott (1999) described several littoral cells in the study area which are framed by cuspate forelands, rocky headlands and reefs. They note that a limestone reef located in the offshore zone also acts as a barrier to incoming swells and can influence the wave energy, water level and water circulation in the near-shore zone. Closed cell circulation of coastal sediment occurs if a reef extends from one rocky headland to another along the coast in such a way that the sediment is trapped within the lagoonal basin. Open cell circulation occurs if there is a gap in the reef system, also known as an energy window, which allows for sediment exchange between the adjacent near-shore compartments and offshore. Open cell circulation means there is always a loss of sediment to adjoining cells or to deep offshore environments.

The Western Australian Planning Commission (WAPC 2003) has noted that there are two potentially closed cell systems respectively north and south of Jurien Bay. In both of these sites, the coast is sheltered by the offshore reef system and that approaches the shore at northern and southern ends.

The offshore reef can prevent 60 per cent of the wave energy reaching the coast. Located between the reef and the coast is the inner shelf plain which is a smooth, gentle slope. A combination of the limestone reef, islands, ridges and shallow banks shelter the coast from wave energy so that cuspate forelands, tombolos, embayments and sheltered sandy beaches and lagoons can develop (Richardson et al 2005). The term tombolo is applied to a sand spit that links a reef or offshore island with the coast. A cuspate foreland is a landform that has been developed as an accumulation of coastal sediment protruding from the shore by the longshore transport of sediment through opposing drifts or by wave refraction around offshore islands (eg. Island Point). These features all interact with the supply of sand to the beaches and therefore influence dune formation and mobility.

Coastal landforms include river mouths. There are few rivers located within the study area. The mouths of the Greenough and Irwin Rivers are blocked by sediments for half of the year due to the southward longshore drift of sand along the beach (Sanderson and Elliott 1999). The Hill River mouth is blocked intermittently by northward longshore drift.

All of these features can enhance or reduce the supply of sand from offshore onto the beaches and influence sand dune formation (Figure 23).

Coastal environments are highly dynamic and complex because they are influenced by various high-energy weather elements such as air pressure, wind, temperature, precipitation, waves and swell, sea level conditions, tides and currents. The Leeuwin Current system is one such element influencing coastal environments located off the study area. This system consists of three major currents – the Leeuwin Current, the Leeuwin Undercurrent and the Cape Current. The Leeuwin Current is a poleward-migrating tropical current of the Indian Ocean that hugs the west coast of Australia. It’s less than 100km wide and approximately 300m deep. The water in the Leeuwin Current has a lower salinity than the surrounding water and is migrating at 1m/s. It is stronger in winter than in summer as during the summer months the Leeuwin Current is pushed offshore. Strong southerly winds create the Cape Current, a northward flowing shelf current system which is up to 20km wide. This is a wind-driven current that exists from November until March, bringing in cold, nutrient-rich water which plays an important role for the local fishing industry. The third major current is the Leeuwin Undercurrent which is a northward flowing current that flows below the Leeuwin Current at 200-400m depths (Thompson, 1984; Chua 2002, Woo 2005).

The coast of the study area is influenced by a micro-tidal range of less than 0.5m, a strong southerly sea breeze and a low wave energy (WAPC, 2003). Under high energy wave conditions, such as storm events, the breaking waves carry sand offshore. However, under low energy wave conditions the waves and currents deposit the sand directly from the shore face to the beach. Bird (1984) published several methods on how sand can be accumulated on a beach and Aagaard et al (2004) described how longshore drift can lead to a net build-up of beach sediment. Such methods include the sand supply coming directly from the eroded coast itself, fluvial sediments from river mouths or biogenic calcareous sediments from the ocean via shoreward transportation.

The beach sediments and sand dunes in the study area, as noted earlier, are composed dominantly of fragmented and broken-down biogenic material such as bryozoans, molluscs, foraminifers and calcareous algae. The calcareous sand demonstrates the shoreward transportation of the biogenic material living offshore as far as the continental shelf. However, the transport of sand shoreward, especially during successive marine transgressive cycles, depends on several factors such as sea floor topography, wave energy and the presence or absence of submarine vegetation (Bird 1984). The sediments on the beach and sand dunes consist of at least 70 per cent of marine-derived organic carbonate detritus from the reef which were transported shoreward. The reasons for the high percentage of carbonate in the study area are aridity of the land, the presence of only a few rivers that transport little detritus from the hinterland, a low wave-energy system that is insufficient to transport the fluvial sediments back to the shore, and a rich marine ecosystem.

The biogenic material lives on the deeper inner continental shelf at depths of up to 70m and in sea grass which grows in shallow waters close to the shore. Both of these sites provide a favourable habitat for molluscs, foraminifera and algae and the biogenic material can be eroded and transported shoreward to form low-energy beaches (Figure 23). Longshore currents in the near-shore zone transport sediments along the beach, known as a littoral drift, with the sediments accumulating against headlands and groynes (WAPC 2003). Littoral sand transport is predominantly caused by wind waves generated by the sea breezes. Richardson et al (2005) documented the sea breezes that blow onshore and generate these waves, and they have velocities in the range of 20-28km/h. The sheltered location of the study area provided by the limestone reef is the reason for the low-energy waves that are the main cause of sedimentation on the sandy beaches and the dunes.

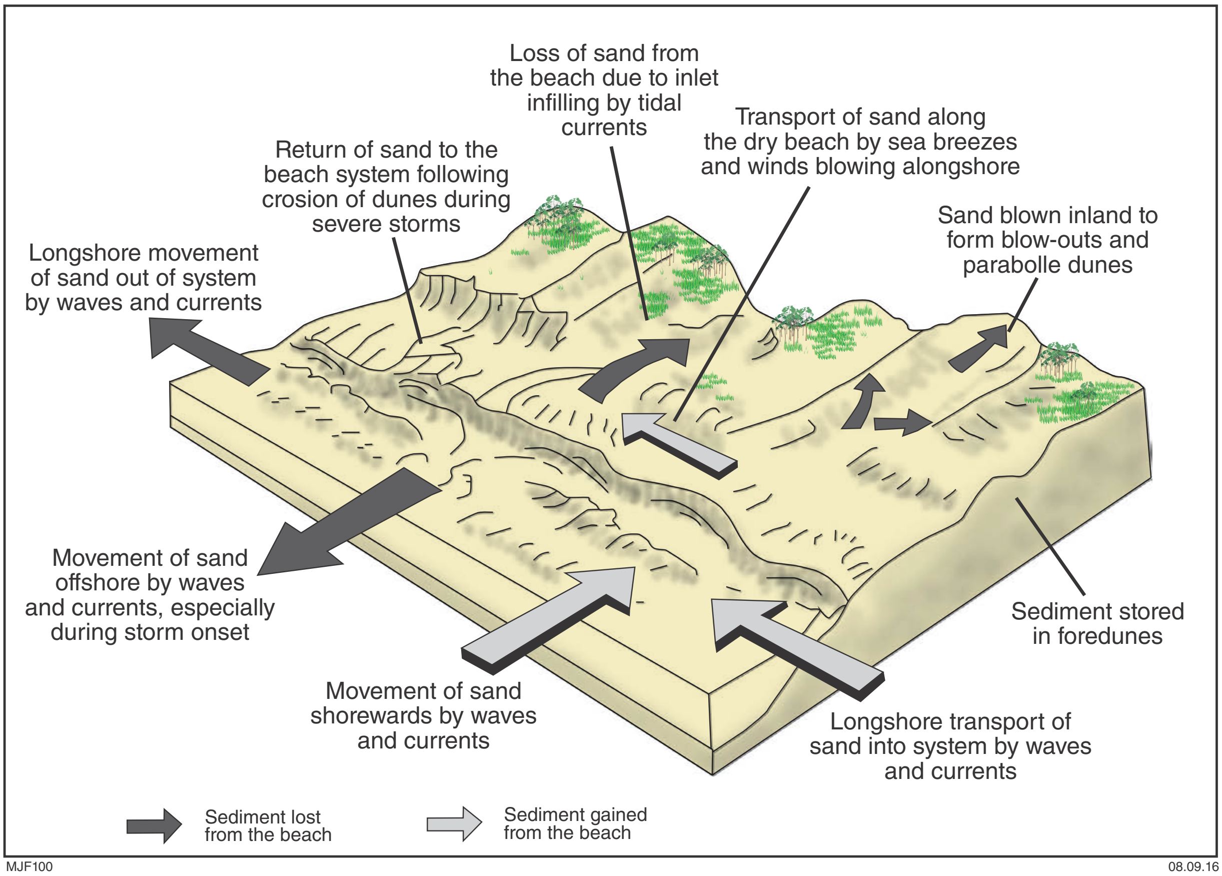



**Figure 23. Components of coastal sediment budgets (Western Australian Planning Commission, 2003)**

The dunes located in the south of the study area are larger than the dunes in the north which is inferred to relate primarily to the sediment supply. This interpretation was supported by Sanderson and Elliott (1999) who divided the study area into a northern and a southern zone at Green Head. Sanderson and Elliott described the area north of Green Head as one of rocky headlands and outcrops, pocket beaches and shallow lagoonal waters with an average depth under 5m. The reef has a higher elevation but is situated further offshore (5-10km) compared with the southern zone. These factors result in a smaller surf zone, lower wave energy and a narrower beach width (less than 20m). South of Green Head the reef is situated only 2-4km offshore but is more perforated and deeper than in the north with a depth of 5-10m. Therefore, in the south of the study area, sandy beaches are longer and there are fewer large cuspate forelands of Holocene age (Sanderson and Elliott 1999).

## Dune impacts on infrastructure and consideration of some solutions

In the study area a number of dunes have or will have impacts on built structures and developments. Table 4 lists features within the study area that are vulnerable and provides estimates of times until the potential impacts. These times are determined from both the 50-year average speed and also from the speed determined for Period 3. As noted above, there has been significant variation in the dune speeds and these estimated times are therefore highly vulnerable to change. There is no certainty that the historic rates will persist; the dune speeds may accelerate or decelerate. This imprecision is emphasised in the table where there was significant difference between the overall average speed and the Period 3 speed by showing marked differences in the times of impact.

Bovin & Jonsson (2011) describe sand dunes as natural hazards which can cause major material and socio-economic damage. The dune sands blow over roads, highways and railways and can even bury settlements. In the late 1800s, the town of Eucla, located on the south coast of Western Australia near to the South Australian border, was buried by shifting sand dunes. The ruins at the site of the town now constitute a historical tourist attraction.

The migration of sand dunes is a slow and pervasive geomorphologic event that has consequences for human welfare as the removal of sand from affected infrastructure imposes significant costs on the community and the relevant government authorities. Kailis Drive is currently being impacted by the Dongara West mobile sand dune and the Indian Ocean Drive may be impacted in the next few years by the Grey Dune. However, several other roads will be impacted soon by the migration of dunes, eg. the Wedge Island Road, in the longer term. Once the sand has blown onto the roads it can become a safety hazard that at minimum causes delays and at worst can create road hazards and incur economic loss (Bovin & Jonsson 2011).

Bovin & Jonsson (2011) provide several methods to reduce or stop sand dune migration or provide solutions for infrastructure already damaged. Mobile sand dunes can be slowed or halted by increasing the critical roughness density of the dune surface which will decrease the sand transport capability (Gillies et al. 2011). As roughness increases the ground-level, wind speed decreases which in turn decreases saltation flux. Dong (2004), in considering stabilisation of dunes in the Taklimakan desert, identified the prime fixation technique as mechanical dune stabilisation by fences. Fences that are set up directly across the path of the prevailing wind halt or slow the rate of sand movement because they act as artificial barriers causing sand accumulation at the lee site. The wind in the study area is coming from various directions, so to apply this method here would require fences to be set up as squares creating a checkerboard effect. For example, in Mauritania "close clustered reed fences" with a porosity of less than 10 per cent proved the most effective (Dong 2004).

Another temporary roughness option is to use a straw checkerboard technique which has already been proven as an effective method in China (Figure 24). The straw checkerboard technique was developed by scientists from the Shapotou Desert Research Station in 1957. Rice, wheat or other plants were planted in a checkerboard pattern. By setting up the semi-covered straw checkerboards, the straw is placed vertically. With the heights of the straw between 10 and 20cm, half of the straws are buried in the sand and half are exposed and the grid size ranges from 1x1 to 2x2m. Smaller grid sizes are required in areas of stronger winds (DRI 2011). Straw checkerboards with a height of 10-20cm and a grid size of 1x1m have been proven to be the most effective. In areas with precipitation of more than 200mm, vegetation should be planted simultaneously (Qiu et al 2004).

Table 4. POTENTIAL Dune impacts on features in the study area

| DUNE | Infrastructure at risk | Distance to infrastructure in 2011 (m) | Migration rate (m/year ) | | Estimated width of dune on first arrival (m) | Maximum width (m) | Maximum height (m) | Indicative timing of dune impact (year) | |
|---|---|---|---|---|---|---|---|---|---|
| | | | For period 2001–10 | For period 1960–2010 | | | | At speed for period 2001–10 | At speed for period 1960–2010 |
| Southgate | Brand Highway | 150 | 12.7 | 6.8 | 30 | 1,200 | 6 | 12 | 22 |
| | Houses in Wandina | 200 | 12.7 | 6.8 | 30 | 1,200 | 4 | 16 | 30 |
| Dongara West | Kailis Drive | 0 | 8.0 | 7.7 | 120 | 300 | 10 | Now | Now |
| Dongara East | Kailis Drive | 130 | 2.2 | 4.1 | 20 | 370 | 10 | 60 | 31 |
| White Point | Dongara-Eneabba railway line | 380 | 20.2 | 11.9 | 25 | 790 | 18 | 19 | 32 |
| Illawong | Indian Ocean Drive | 1,000 | 30.4 | 9.4 | 30 | 740 | 4 | 33 | 105 |
| Coolimba | Indian Ocean Drive | 500 | 6.4 | 7.7 | 50 | 560 | 7 | 78 | 65 |
| Green Head North | Scenic tourist road | 140 | 17.7 | 8.5 | 30 | 260 | 3 | 8 | 16 |
| Green Head South | Indian Ocean Drive | 480 | 15.5 | 12.5 | 30 | 1,400 | 4 | 30 | 38 |
| Grey | Indian Ocean Drive | 250 | 17.9 | 15.7 | 100 | 1,700 | 10 | 13 | 16 |
| Wedge Island South | Road into Wedge Island | 215 | 18.9 | 10.6 | 70 | 800 | 3 | 11 | 20 |
| Wedge Island East | Indian Ocean Drive | 900 | 11.1 | 11.2 | 30 | 2,100 | 11 | 80 | 80 |

Figure 24. Straw checkerboard technique (DRI 2011) and its application on the Tarim Highway, China (The Tarim Highway, undated).

The checkerboard technique described above was conceived on the basis of it commencing a progression of vegetation growth that can take up to five years to become properly established and thus lead to a healthy vegetation succession. The first vegetation growth of grasses is followed by shrubs and finally woodland or heath. This environmentally friendly method can halt the sand movement as long as the plants used for brushing meet certain requirements. These requirements include being resistant to strong, hot and dry winds and in the near-coast environment on sand the vegetation must tolerate salty conditions (halophytic plants) and nutrient-poor environments (Goudie 2010).

Goudie (2010) states that the mechanical removal of sand is also an effective method of mitigating the impacts of mobile sand dunes. While this may seem a pragmatic approach, the quantity of sand moving in larger dunes each year can be very large and invoke considerable community expense. However, in Western Australia the sand has a high component of lime and is a very marketable commodity for farm applications. Therefore, extracting and utilising the limesand is playing a crucial role in stopping a number of the dunes from migrating or at the very least minimising the damage by removing the limesand.

The optimum solution is to extract the limesand from the head of the dune at a rate near or above the rate at which the dune is migrating. Marketing of this product for farm application to control farm soil acidity actually utilises the economic value of the sand to overcome the economic cost of managing the migrating sand. Other techniques of management involve significant cost, to the financial detriment of either the State Government or Local Government authorities.

# Dunes along the Mid West coast

## Southgate Dune

The Southgate Dune, located 7km south of the centre of Geraldton, is migrating northwards on freehold and unallocated Crown land. On the freehold, limesand is not a mineral and extraction is subject to Local Government authority through grant of an Extractive Industry Licence. Southgate dune covers 194ha and is up to 6m high. It has advanced to the edge of a beach access track from which extraction of the limesand is proceeding and appears to be holding the dune head nearly stationary, although it is not clear if sufficient extraction is occurring to stop the dune sand (Figure 25).

Since 1960, Southgate Dune has decreased in area from nearly 300ha to nearly 200ha. This has been caused by the natural stabilisation of the tail parts of the dune, particularly with the flanks becoming stable. It has averaged 6.8m/year of advance at the head, the speed having decreased markedly from Period 1 (8.9m/year) to Period 2 (3.6m/year) but then accelerated markedly in Period 3 (12.7m/year). This acceleration is of concern because if it maintains this speed, the dune will present a geohazard to the Brand Highway and the houses in Wandina. Alternatively, it will require the removal of larger quantities of mobile sand to artificially stop the dune head from moving northwards. However, note the caution expressed earlier in this report that the longer-term speed appears to be a more robust predictor of future average speeds.

The northern 25 per cent of the mobile dune is on freehold land and the remaining southern part is on unallocated Crown land that was proposed in the late 1990s to be converted to freehold. It is recommended that the City of Greater Geraldton monitor the movement of the dune to ascertain if it does pose this threat. The first sign will be the dune crossing the beach access track and entering the freehold property to the north. Successive high waves of sand are approaching from the south and would pose significant costs to remove artificially. Alternatively, stabilisation of the dune south of the head could be caused by vegetating the sand or applying one of the techniques discussed above. However, a public authority considering action will need support from the owner of the land.

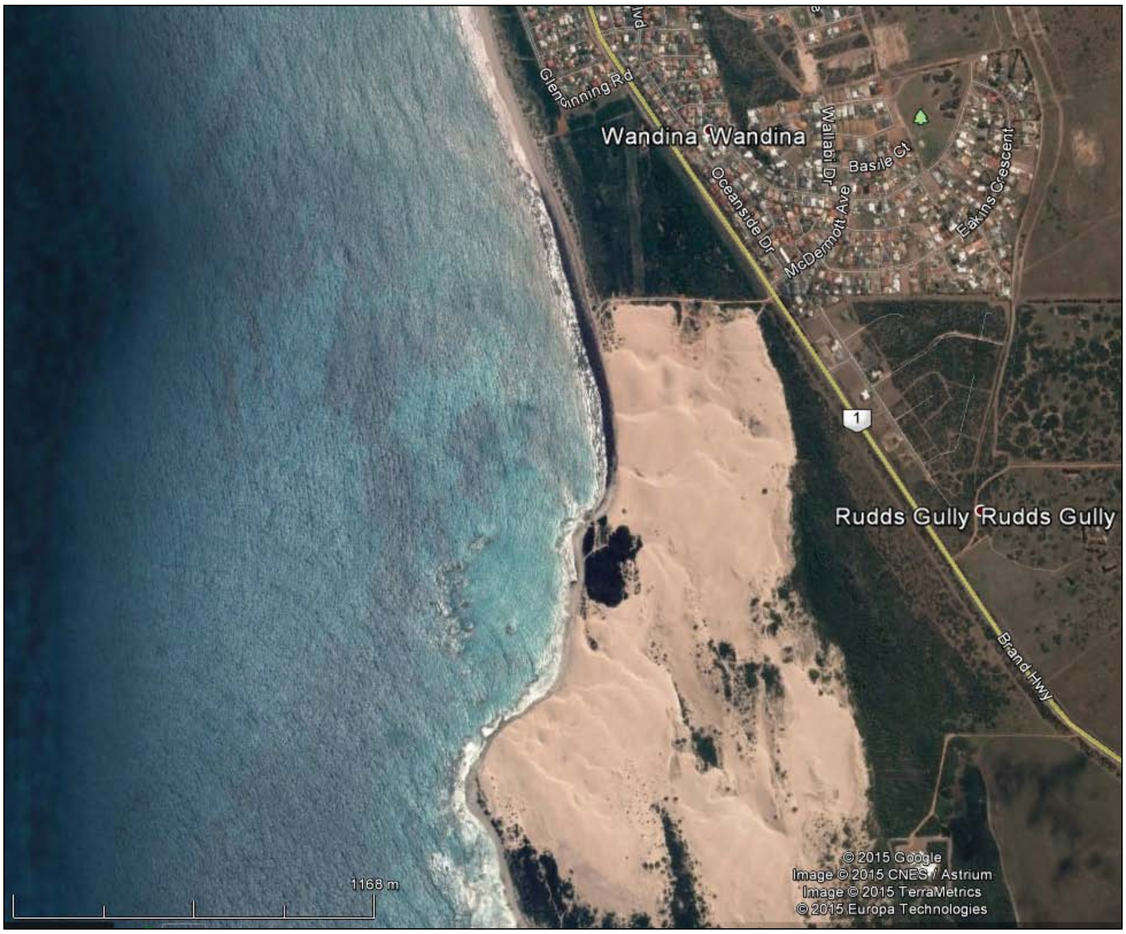



**Figure 25. Southgate Dune showing proximity to Brand Highway and Wandina subdivision houses. The dune head currently runs along the edge of beach track. Map data: Google, © 2015 CNES/Astrium.**

## Cape Burney dunes

The Cape Burney sand dune (Figure 26) is situated 420m south of the Greenough River mouth and centred about 4km south of the Southgate Dune. This limesand dune in 2012 had an area of 60ha and a height of about 4m. In Period 3 it was migrating north-northwest at 10.1 m/year, having accelerated from 3.5m/year in Period 1, has progressively shrunk from 170ha in 1960, and will soon blow sand into the Greenough River. Blockage of the river may then ensue. However, if river flows are strong, it may maintain its course rather than be blocked. It is recommended that the potential problems be considered and taken into account by the City of Greater Geraldton when making nearby land-use planning and development decisions adjacent to the watercourse.

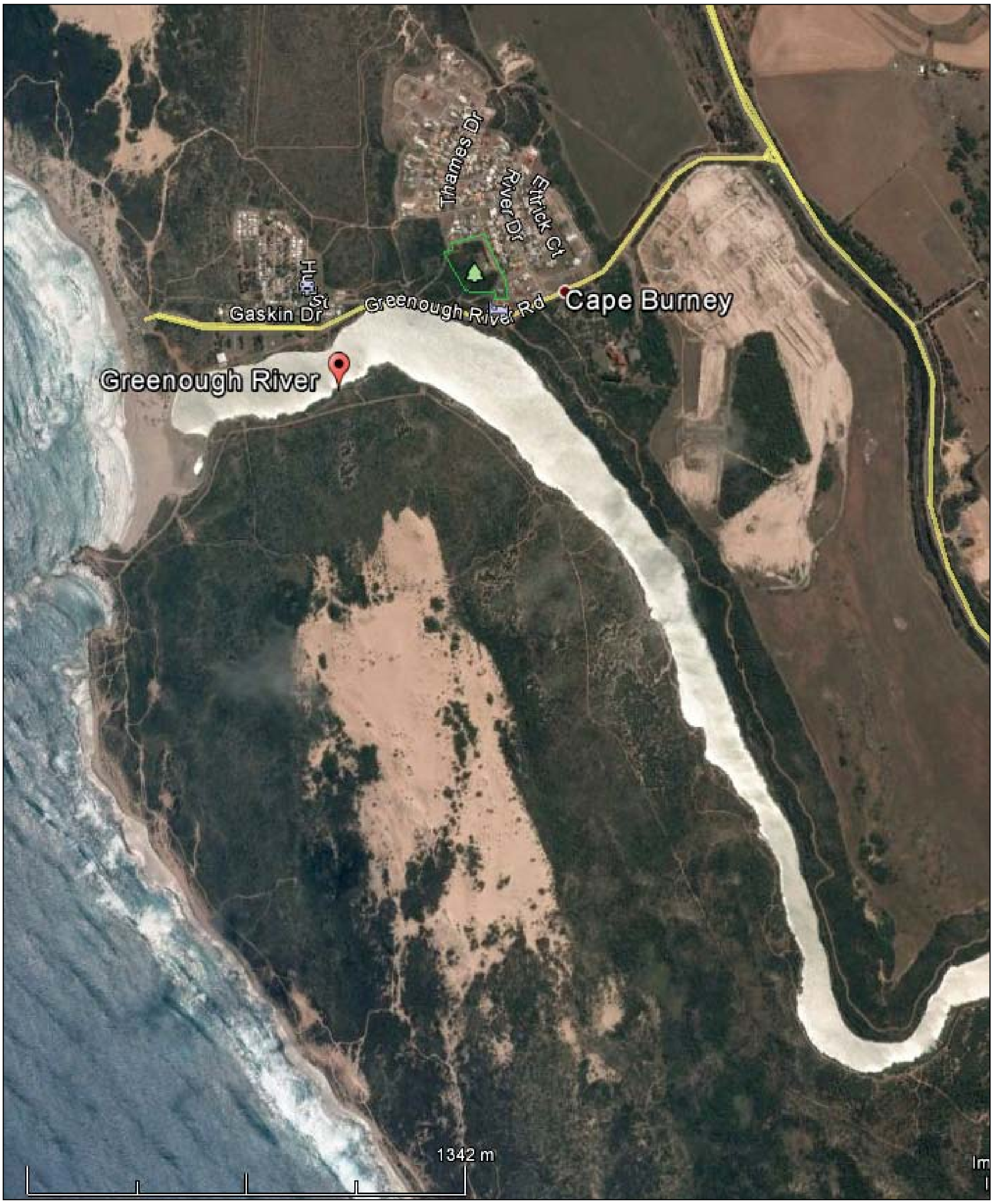



**Figure 26. Cape Burney Dune showing proximity to the Greenough River and its mouth. Map data: Google, © 2015 CNES/Astrium.**

## Dongara dunes

At Dongara the study focused on two dunes, Dongara East and Dongara West, located 7km south of Dongara township.

**The Dongara West dune** has migrated onto and is depositing sand over Kailis Drive (Figure 27). This dune is up to 11m tall and from 1960 to 2001 it decreased in area from 26ha to 20ha, but did not change thereafter. This suggests that the sand will continue to blow at the measured rate of between 7m/year and 8m/year for the foreseeable future. Kailis Drive is a Shire of Irwin road and the sand removal falls under the maintenance responsibilities of that Shire. Figure 28 shows the very leading edge of the dune about to impinge on the road shoulder in October 2004. Figure 29 shows how the dune front had progressed by November 2009 and at that stage the Shire of Irwin had periodically been removing sand from the road. Mining Lease M70/1271, applied for in 2006 and granted in December 2015 over the dune head, should assist through removing and marketing the limesand to sell to farmers, removing the economic liability on the Shire. An example supporting this option is the granted mining leases on the Coolimba and Lancelin dunes where active mining of those dunes has significantly reduced the migration rate and area over the past 50 years. North of this dune, across Kailis Drive, is a limesand processing operation where high-grade limesand is converted to quicklime.

**Dongara East Dune,** located 2km east of Dongara West, is approximately 10m high and between 1960 and 2010 it split into four dunes, and in that time shrank and slowed. In Period 1 it was moving north-northeast at 4.5m/year, but slowed to 2.2m/y in Period 3 while decreasing from 41ha to 14ha. It is considered likely that the dune may cease to migrate before it reaches Kailis Drive, some 120m ahead of the front of the dune. Limesand is being extracted at a low rate from the northeastern corner of the dune where the sand has blown onto freehold land. This extraction is authorised by an Extractive Industry Licence granted by the Shire of Irwin.

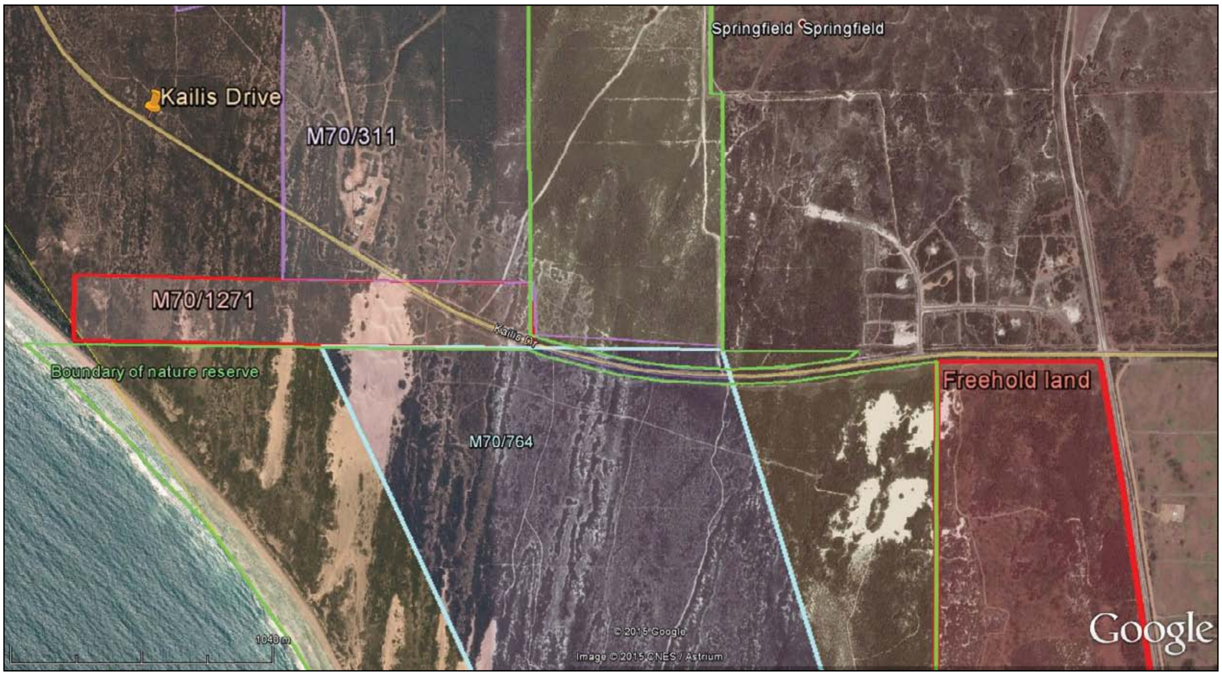



**Figure 27. Dongara dunes (West and East). West has intersected Kailis Drive and East has broken into a number of parts. Note general trend of former dunes that are now stabilised and covered with vegetation. Map data: Google, © 2016 CNES/Astrium.**

Figure 28. Dongara West Dune approaching Kailis Drive October 2004. Photo taken looking southeast.

Figure 29. Dongara West Dune on edge of Kailis Drive, November 2009. Photo taken looking southwest.

## White Point dunes

There are four separate dunes at White Point (Figure 30) that are moving independently towards the north-northeast. The western two clearly show the stabilisation and revegetation of lands behind the dunes. The eastern dune head is 4.9km from the beach and if it had maintained a rate of 20m/year, it would be over 400 years since initiation of this dune, showing the long-term nature of the mobility of these coastal dunes. The western dune has two separate lobes, and the eastern lobe has advanced 1.4km further than the western lobe. In Period 1 and Period 2 of the study, the average speed was approximately 10m/year. However in Period 3 the rate doubled to 20.2m/year. Simultaneously, the area of the dunes decreased from a total of 483ha in 1960 to 254ha in 2010 and therefore the increase in speed of this dune is in contrast to most other dunes where the migration rate decreased as the dunes shrank.

The eastern dune head is 380m from the Dongara-Eneabba railway line and, at an average speed of 11.9m/year, will be approaching the line in 30 years. This is a large dune that is up to 18m high and is expected to continue migrating for many years. It is recommended that monitoring of the dune be undertaken each five years to continue investigating the likely interruption of rail usage.

Mining Leases 70/642 and 70/711 exist over the majority of the dunes. Extraction previously occurred on M70/642 between 1997 and 2001 and on M70/711 between 1994 and 1996. Extraction from M70/642 ceased as the operator has an alternative feed source. However, if the closure of the railway poses an economic threat, it is recommended that the Public Transport Authority engage with the tenement holder to ascertain if any joint amelioration actions could be entertained.

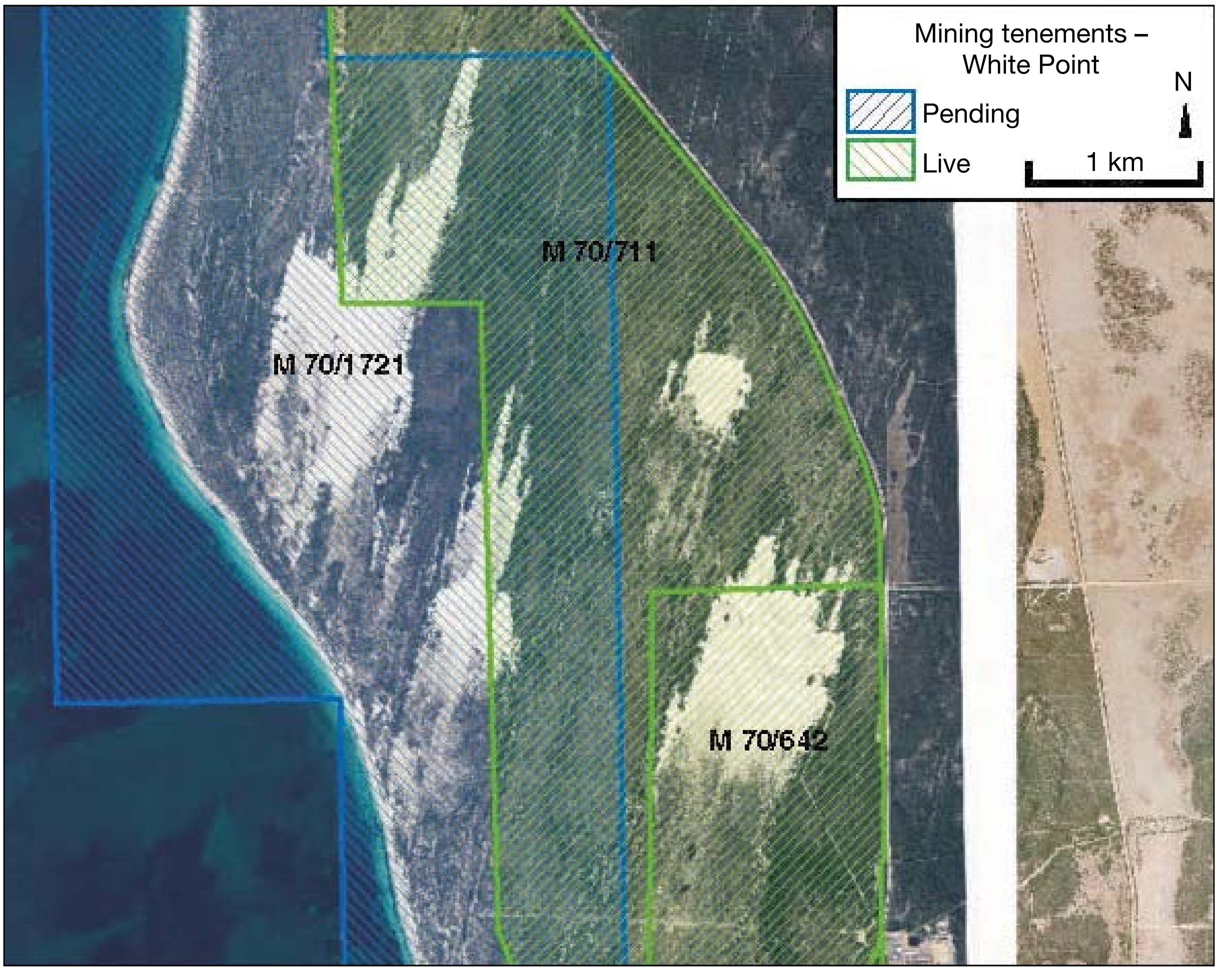



**Figure 30. Four dunes at White Point. Map data: Google, © 2016 CNES/Astrium.**

## Illawong dunes

There are two relatively large dunes at Illawong, both having areas in the order of 100ha, although only the northern was studied in this project (Figure 31). The northern dune is approximately 5km south of the former coastal community of Illawong. This dune is still being fed with beach sand and this is confirmed by the dune area increasing from approximately 100ha to 110ha between 1960 and 2010 as additional sand was fed into the tail of the dune off the beach. In contrast, the southern dune has separated from the beach supply. Both dunes are migrating north-northeasterly. Illawong Dune accelerated markedly between Period 1 and Period 3 from 6.0m/year to 30.4m/year.

At the closest, the head of the northern dune is some 1000m from intersecting Indian Ocean Drive. Both dunes are on Reserve 42 477 for Parkland, Recreation and the Letting of Cottages managed by the Shire of Carnamah. North and east of this reserve and across Indian Ocean Drive, the land is part of the Beekeepers Nature Reserve. At the current rate of movement the dune will not reach Indian Ocean Drive for more than 30 years. Provided the dune maintains the average speed of 9.4m/year as recorded for the period 1960 to 2010 it will be a century before this impact occurs.

The northern dune is largely within the area of the application for Exploration Licence 70/2221, although the head is close to blowing out of the tenement application area. The southern dune is on application for Exploration Licence 70/4652. Exploration licence E70/2221 over the dune will not allow for the removal of sand. It would be beneficial to grant a mining lease over this dune as, if migration is not addressed, it could start to impact on Indian Ocean Drive over the next 30 years. It is recommended that the dune be monitored each five years in order to allow time to prepare and address the complications of any impact.

## Coolimba Dune

The Coolimba dune (Figure 32) consists of a large western dune, with an area of over 70ha and a height of up to 7m and a smaller eastern dune with an area of less than 10ha; both had separated from a single large dune historically.

Coolimba Dune in 1960 covered 89ha which increased to 91ha in 1982, but then decreased to 71ha in 2006. This change in area correlates with the speed of the dune, rising from 7.4m/year in Period 1 to 8.36m/year in Period 2 and then slowing to 6.4m/year in Period 3.

The dunes are centred some 4km north-northwest of the intersection of Indian Ocean Drive and Coolimba-Eneabba Road and are migrating north-northeast towards Indian Ocean Drive. The eastern dune is becoming stabilised with vegetation and is likely to stop moving before it has gone much further. However the larger western dune is considered likely to continue migrating and if it maintains the speed in Period 3, it will cover the 500m to reach the Indian Ocean Drive in just over 75 years.

The majority of the dune is within M70/932 and limesand production is proceeding from an area some 500m back from the head of the dune. Continued extraction of the limesand will assist in removing sand that is migrating and will probably slow the movement. Access to the dune is along Miscellaneous Licence 70/75. It is recommended that the migration of the dune be monitored to provide early warning to Main Roads WA if it seems likely to impact on Indian Ocean Drive.

## Green Head dunes

Two dunes were studied at Green Head, one north of the townsite and a second south. Green Head North (Figure 33), with an area of 28ha, is up to 3m high and centred 3km north of Green Head, is of particular concern as its migration rate has accelerated from about 7m/year in Period 1 and Period 2 to 17.7m/year in Period 3. At the same time, its area has remained at between 24ha and 28ha. It is inferred that it will continue migrating for some years. The sand dune is currently only 140m from a local beach access road and, if not addressed, within a couple of years this dune will meet and potentially cut the scenic tourist route. This dune is on a reserve for Parkland, Recreation and the Letting of Cottages managed by the Shire of Coorow and therefore maintaining the tourist road will be a Shire responsibility.

A prospecting licence (P70/1468) has been applied for over the dune. However, it is reported that there is community opposition to the grant of the tenement and potential extraction of limesand. Grant of this tenement

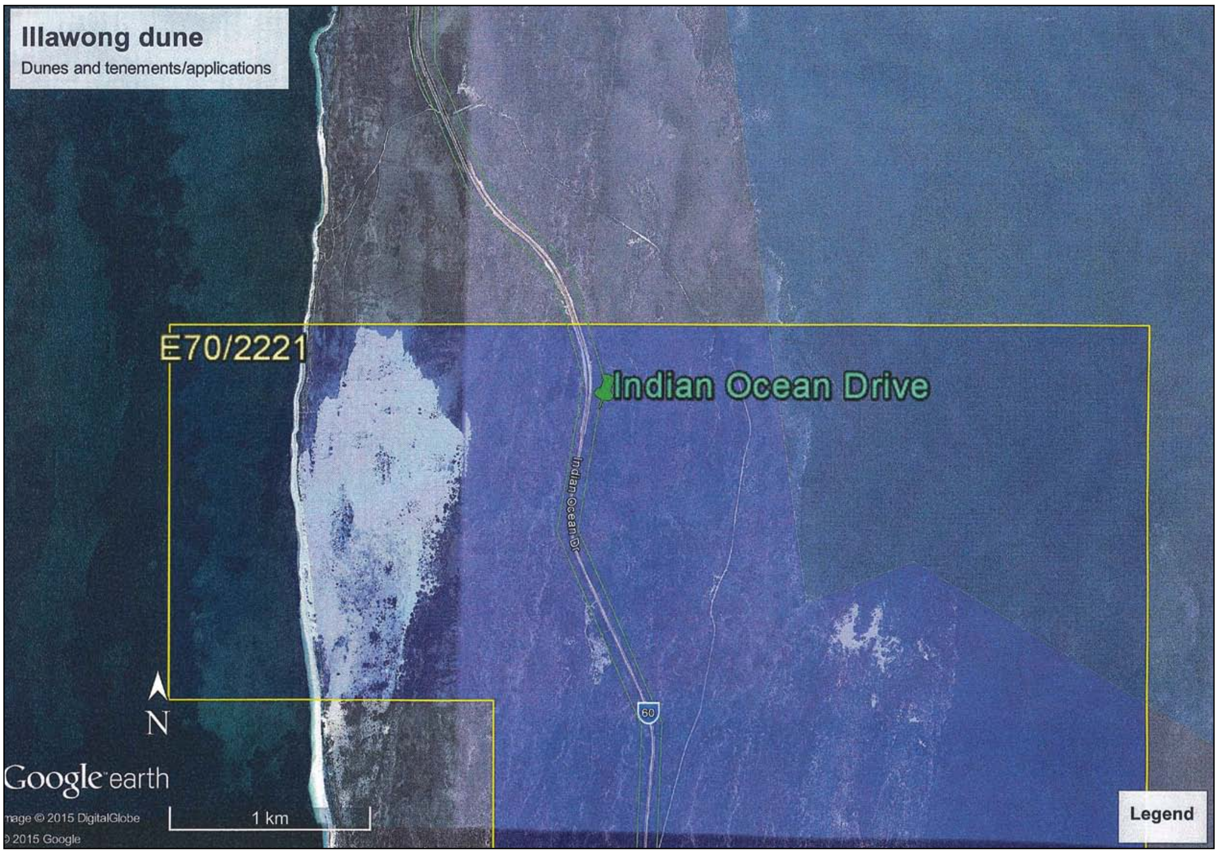



Figure 31. Illawong northern dune showing extent of exploration licence 70/2221. Indian Ocean Drive is the light-coloured line east of the dune. Map data: Google, © 2016 CNES/Astrium.

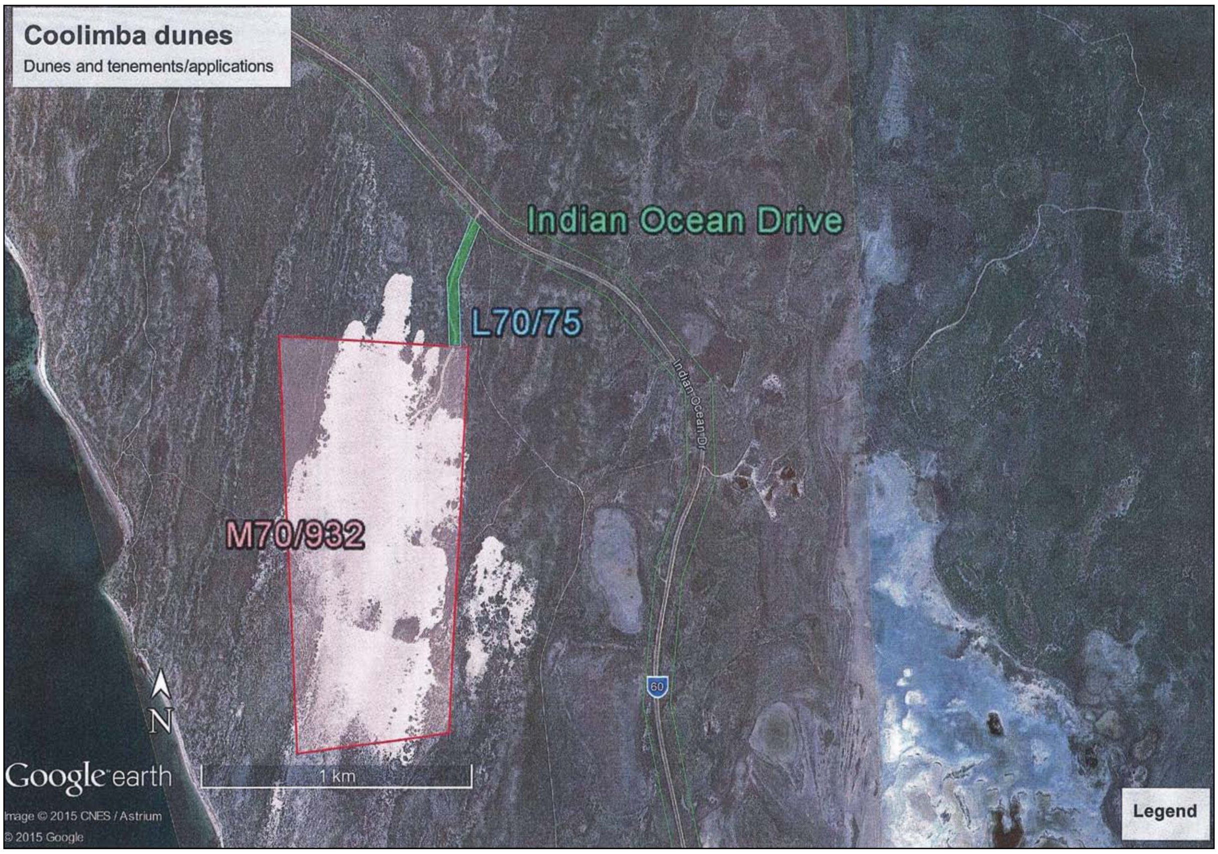



Figure 32. Mining tenements on Coolimba Dune. Indian Ocean Drive is the light-coloured line to the east and north of the dune. Map data: Google, © 2016 CNES/Astrium.

will not permit productive extraction and a mining lease will be required for that activity to be authorised. If productive extraction under authority of the Mining Act is not undertaken, the Shire of Coorow will have to undertake removal of sand blowing over the road at its expense. Remediation of this geohazard is likely to be required in the near future.

Green Head South Dune (Figure 34), located 5km southeast of Green Head, is a moderately large dune (174ha) and up to 4m high that is progressing on a broad front with several leading nodes. It is migrating slightly east of northwards, and has changed speed markedly from 16m/year in the first study period, slowing to half that in the second period and then returning to the original speed in the third period. At the closest, it is nearly 500m from Indian Ocean Drive and could intersect that in 30 years. However, extraction of limesand from behind the dune head is likely to lead to that part of the dune slowing and possibly not reaching the highway. Other nodes of the dune may continue migrating towards the road and future monitoring of that progress is recommended in five-year intervals. Tenements exist over other parts of the dune and extraction on those would assist in reducing any future potential geohazard potential from those parts. The dune is on Parkland and Recreation Reserve 40 544 managed by the Shire of Coorow.

## Sandy Cape Dune

The Sandy Cape Dune (Figure 35) is a moderately large north-migrating dune located 14km north of Jurien Bay. It covers 71ha and is up to 7m high and is now is well separated from the coast at its source. Since leaving the beach, it has migrated approximately 5km. The dune is advancing over previous generations of coastal dunes that are now fixed and vegetated and does not pose any threat to infrastructure except for four-wheel-drive tracks used to access isolated beaches. Sandy Cape Dune is within Reserve 19 206 for Parkland and Recreation managed by the Shire of Dandaragan.

Sandy Cape Dune has contracted markedly from 129ha in 1960 to 71ha in 2010. As with many other dunes, it slowed from 10m/year in Period 1 to 8.1m/year in Period 2 and then accelerated to 22.8m/year in Period 3.

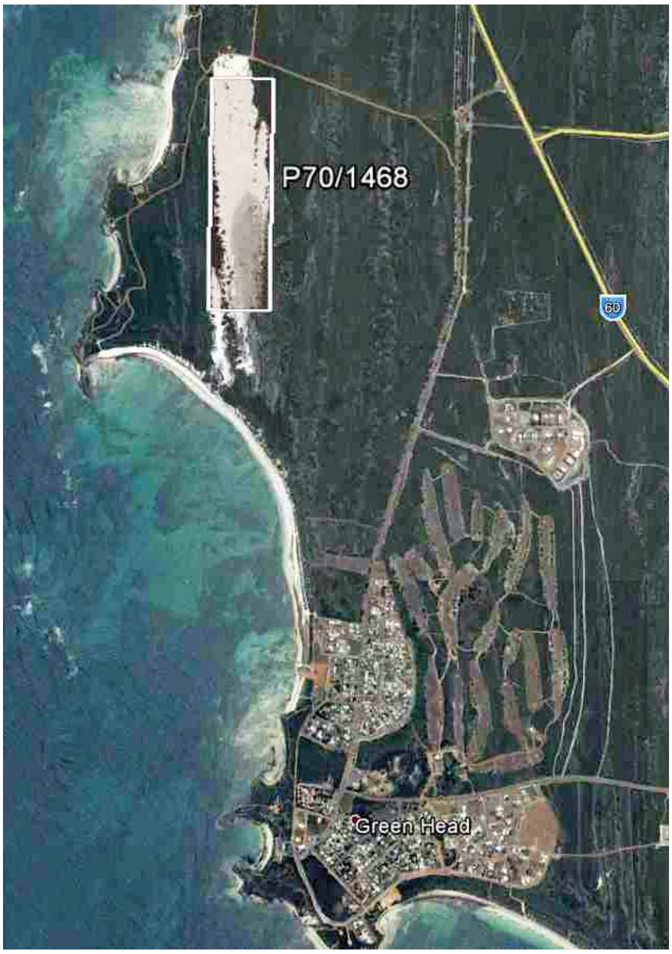



Figure 33. Green Head North Dune, within 140 metres of intersecting the tourist road that accesses bays and beaches near the township. Map data: Google, © 2016 CNES/Astrium.

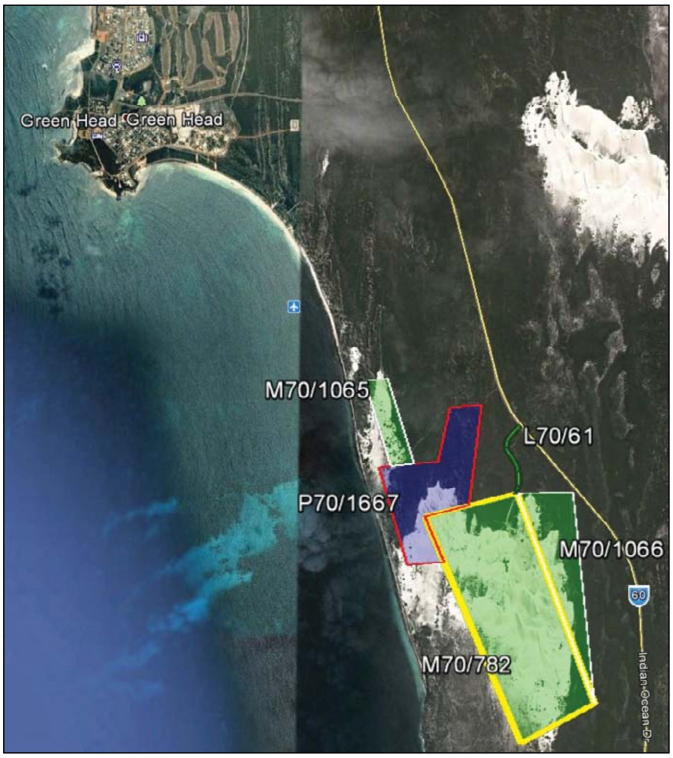



Figure 34. Green Head South Dune showing tenements. Green tenements are granted and the blue is an application.
Map data: Google, © 2015 CNES/Astrium.

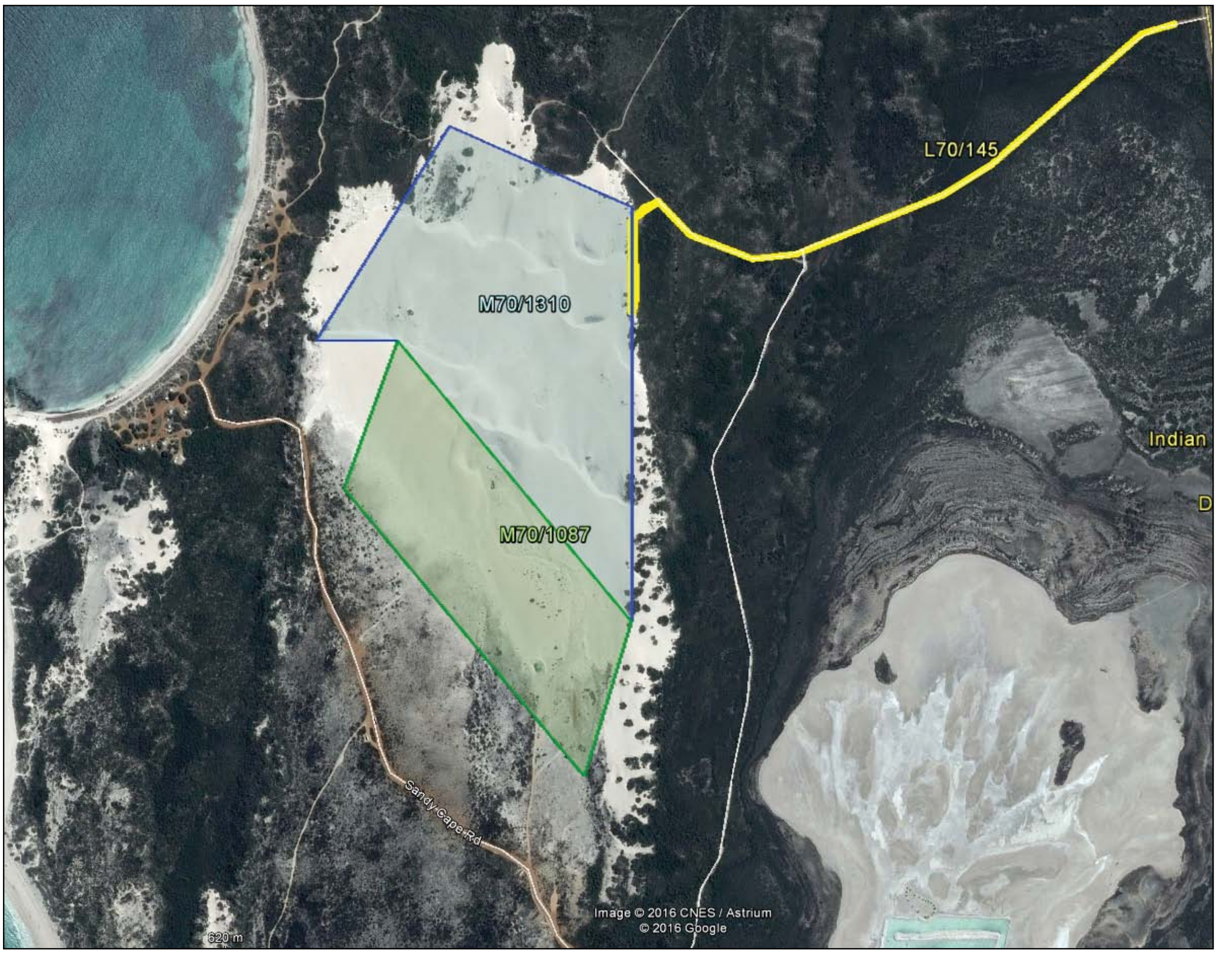



**Figure 35. Sandy Cape Dune and tenements. Green lease is granted, blue is application and yellow is miscellaneous licence for access from Indian Ocean Drive. Map data: Google, © 2015 CNES/Astrium.**

The tail of the dune has vegetation re-establishing on and stabilising the loose sand. At the head of the dune there is a 250m-wide central lobe that is about 250m ahead of a large wave of sand that extends across the 600m width of the whole mobile sand dune. It is inferred that this dune is the product of an earlier, narrower, central dune that is being overtaken and overcome by the much wider later dune.

Sandy Cape Dune had previously cut across bush tracks that allowed access to coastal recreational sites, more recently replaced by a beach access track across the tail of the dune. Otherwise it does not pose any threats to built infrastructure.

## Grey Dune

This dune (Figure 36) is located immediately northeast of the former coastal settlement of Grey and is within Nambung National Park. Grey Dune currently has an area of nearly 380ha and is over 10m high. It appears to have been migrating from a beach source located at least 14km to the south of the present tail and it is therefore inferred it will continue migrating for several more kilometres over future years and decades. During the study period it has been moving in a north-northwest direction, but its speed is unusual when contrasted with other dunes studied. In Period 1 it was migrating at 10.7m/year and then accelerated in Period 2 to 20.3m/year, finally slowing a little in Period 3 to 17.9m/year. Between 1960 and 2010 it shrank from 577ha to 378ha.

The new scenic tourist route along Indian Ocean Drive was opened on 19 September 2010. However it is located on the migration route of the Grey sand dune. Main Roads Western Australia (MRWA) removed bare dune sand over about a 100m width on the western side of the dune adjacent to the road at the time of road construction in 2009–10. Subsequently, to reduce the visual impact of the bare limestone pavement adjacent to the road as well as trying to minimise the movement of the dune sand, the surface of the area, that had consisted of remnant sub-dune limestone pavement, was covered with topsoil and mulch material that consisted of local vegetation including seeds (Figure 37) . Two years later the vegetation had grown significantly, covering the bare surface (Figure 38).

Following a report from 360 Environment Pty Ltd, tube stock was planted on the dune in winter 2012. To ensure the seeds were representative of the regional flora and would successfully grow on dune limesand, collection was confined to 25km east of the coast and 50km north or south of the Grey Dune. The seeds germinated and seedlings adapted and have since regenerated vegetation that has stabilised the area and reduced the visual impact. Species suitable for the Grey Dune were presented (Table 5) in the report Dune Stabilisation Concept by 360 Environmental (2010).

The dune is adjacent to Indian Ocean Drive, is moving close to the edge of the highway and will encroach on the highway in time. Remediation to remove the sand will become a significant cost because this dune is high (more than 10m) and wide (more than 1700m). Some 350m of width of this dune will intersect the Indian Ocean Drive, presuming it maintains its current path. From calculations, it is estimated the dune has the potential to deposit over 100,000 tonnes of limesand on the road per year. Remnant stabilised dune limbs are apparent adjacent to Grey Dune and continue for up to 5km north of the head of the dune, indicating the potential for the large Grey Dune to continue migrating and impact the highway. It is recommended that Main Roads WA investigate potential options for alleviating this impact in collaboration with the Department of Parks and Wildlife as the dune is within Nambung National Park.

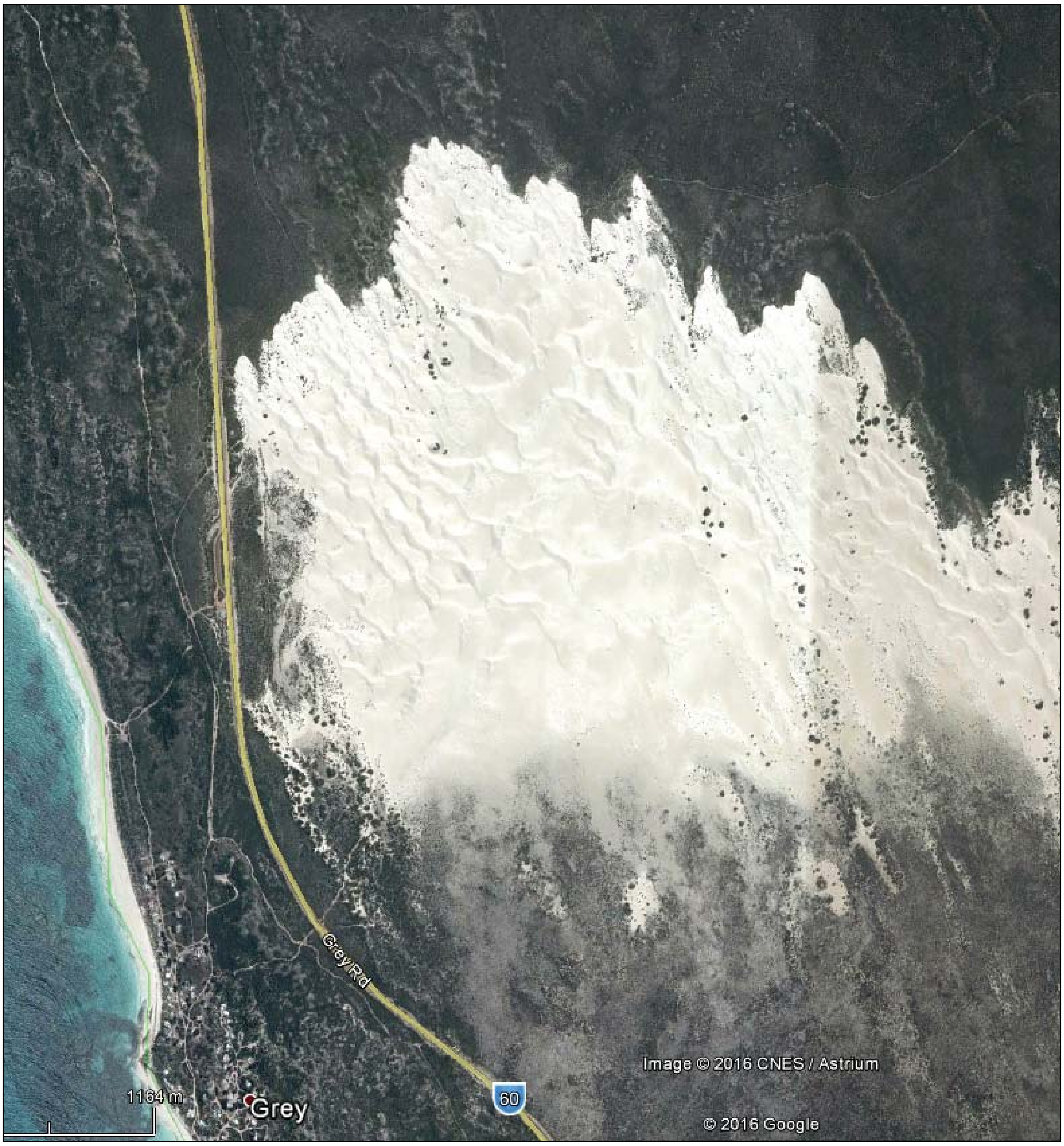



**Figure 36. Grey Dune showing proximity to Indian Ocean Drive and general direction of migration towards the north-northwest. Note that western 350m width of the dune is heading towards intersecting the highway. Map data: Google, © 2015 CNES/Astrium.**

Figure 37. Hundred-metre-wide area from where Grey Dune sand was removed along its western margin prior to building of Indian Ocean Drive, August 2011. ▲

Figure 38. Regrowth of vegetation adjacent to Grey Dune following reseeding and planting of tube stock. Similar to site shown in Figure above, but two years afterwards (August 2013). ▶

Table 5. Suitable native plant species for seeding on the Grey Limesand Dune (360 Environmental, 2010).

| Genus | Species |
|---|---|
| Acacia | cochlearis |
| Acacia | cyclops |
| Acacia | rostellifera |
| Allocasuarina | lehmanniana |
| Atriplex | cinerea |
| Atriplex | isatidea |
| Carpobrotus | virescens |
| Ficinia | nodosa |

| Genus | Species |
|---|---|
| Melaleuca | huegelil |
| Melaleuca | systena |
| Myoporum | insulare |
| Olearia | axillaris |
| Rhagodia | baccata |
| Scaevola | crassifolia |
| Spinifex | longifolius |
| Spyridium | globulosum |

## Wedge Island dunes

Three dunes are recognised, North, South and East (Figure 39). The western two are close to the coastal community of Wedge Island. All three dunes are migrating to the north-northwest and the eastern two have potential implications for roads.

Wedge Island North is migrating away from the nearby community at a velocity of 27m/year during the last study period (2001–10) and does not pose any threat. It is actually migrating towards the beach and will be contributing sand back onto the beach in the very near future.

Wedge Island South is the smallest of the three dunes with an area of 111ha in 2010 and a height of less than three metres. This is migrating towards the newly constructed Wedge Island access road and could intersect that in about 10 years at the latest velocity of 19m/year. However, it is now migrating into a well-vegetated swale that appears to have the potential to contain all the dune sand at a low level and it is considered that this may slow or stop the dune's migration.

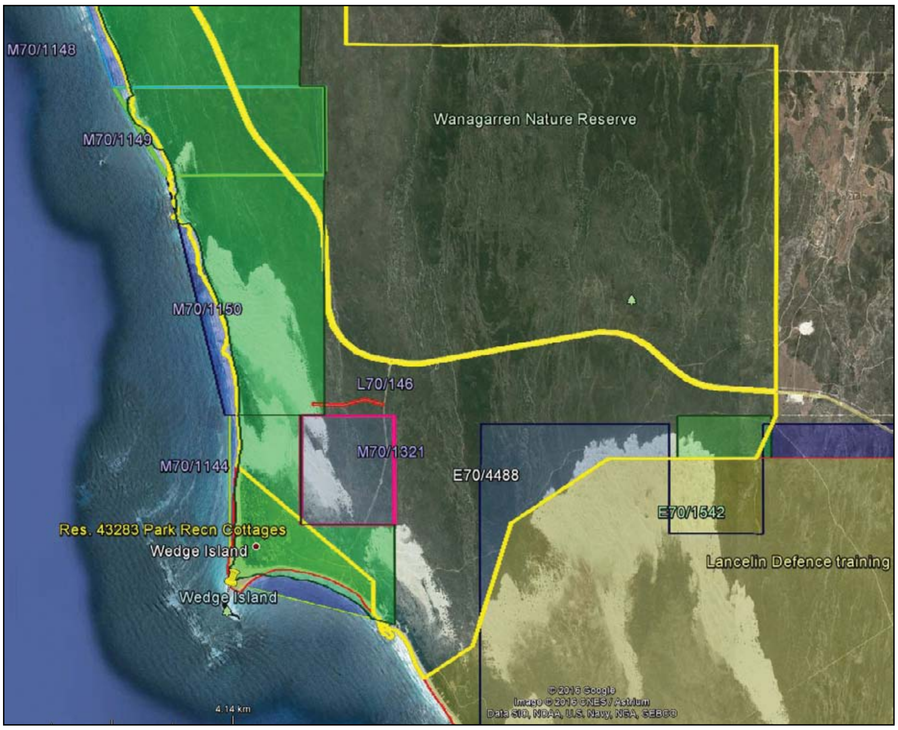



**Figure 39. Wedge Island dunes showing North Dune (upper left), South Dune (in the middle) and East Dune (right-hand) dunes with Mining Act tenements.**
**Map data: Google, © 2014 CNES/Astrium.**

Wedge Island East Dune is the largest dune included in the present study with an area of just over 1000ha, is 2100m wide and up to 11m high. Though it is migrating towards the Indian Ocean Drive, the dune will not intersect it for something like 80 years at the present rate of about 11m/year. It is of note that this dune is one of only three that maintained a consistent rate for each of the three periods studied. However, this is moving at an exceptionally slow speed for its area and this is inferred to be caused by the fact that the dune has been migrating up an incline from about 20m above sea level (ASL) to 110m ASL in its present location (Appendix D). However, from the present position to the Indian Ocean Drive the ground falls to about 45m ASL and consequently there is a possibility that its migration speed may accelerate and the impact on the highway may occur earlier rather than later.

These three dunes are in the Wanagarren Nature Reserve and the Minister for Environment must support any extraction of limesand from the mobile dunes. The East Dune is migrating out of land leased to the Commonwealth Government as part of the Lancelin Defence Training area.

Tenements have been applied for over all of the dunes for the purpose of extracting the limesand. The economically optimum solution to minimising future impacts of the geohazards would be to progress to granting of tenements and consent to extract limesand, particularly from Wedge Island East Dune.

It is recommended that the migration of East Dune be monitored because it would have a major impact on Indian Ocean Drive. The extraction and marketing of the limesand should be supported as a means of reducing future economic impacts on the road, which is a major tourist route.

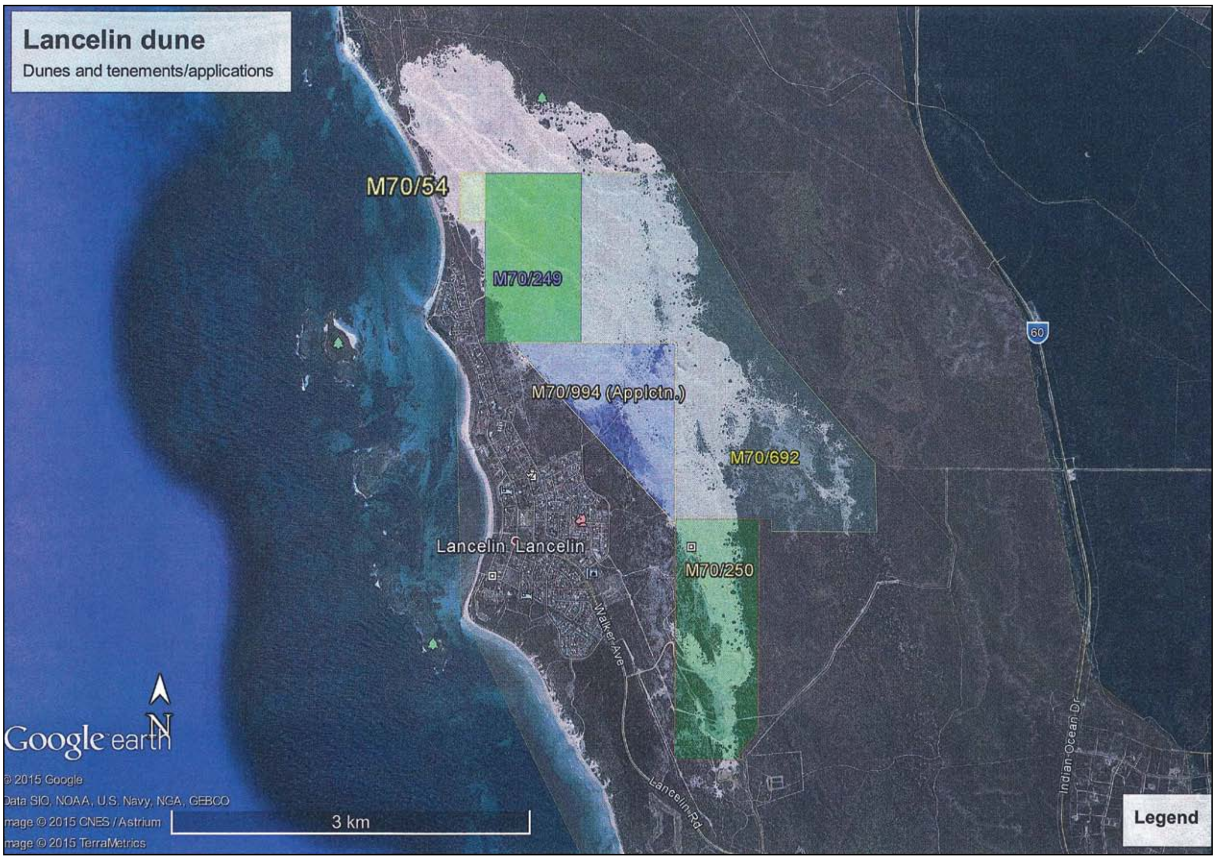



**Figure 40. Mining tenements on Lancelin Dune. Note proximity of housing on south western margin of mobile dune. Current limesand extraction is mostly proceeding in the southern-most portion. Map data: Google, © 2015 CNES/Astrium.**

## Lancelin Dune

The Lancelin Dune (Figure 40), the southern-most dune in the study area, covers a very large area (nearly 700ha), is immediately east of the Lancelin townsite and is well-used for recreational purposes for driving four-wheel-drive motor vehicles, quad-bikes and motorcycles over the bare dunes. As such the community has expressed strong reservations about the ongoing mining of the limesand.

Lancelin Dune has complex morphology and strictly speaking the Lancelin Dune should be referred to as a dune sheet. However, for simplicity in this report it is termed a dune. It is migrating in a north-northwesterly direction. At the northern end it is encroaching onto the beach and the sand is being recycled back into the shoreline environment.

During the study periods, this dune has experienced a significant decrease in its migration rate and area, decreasing in speed from 37.9m/year to 6.1m/year between the first and last periods in the study with a corresponding area decrease of 393ha, representing a 36 per cent change from 1960 to 2010. This decrease has occurred especially on the southwest side mostly near to the extraction areas of limesand. This part of the dune is no longer considered a “mobile dune”. The present extraction activities are located on both the body and limbs of the dune and due to this extraction, the dune limb is now located one kilometre further east than in 1960.

The sand is migrating parallel to the eastern edge of the townsite and within 160m of the nearest houses. Through the reduction in area, this dune no longer impacts on the settlement except when the easterly winds are blowing dust from the bare sand. At times of extreme dryness, such as in summer, dust from the dune could be a nuisance to some residents. Previously, the southern portion of the dune was migrating towards the eastern edge of the townsite, but mining in the southern portion appears to have removed this threat.

## Possible solutions to resolve or reduce dune impacts

Increasing the roughness index of the surface can reduce the wind velocity, reduce its transport capability and in the best cases, stabilise the dune. Once colonising plants are able to grow on the sand dunes, a vegetation succession can start (Refer to Figures 37, 38 and 41). Natural dune vegetation occurring in the study area that can start the colonising process includes herbaceous plants such as *Cakile maritima*, Grey Saltbush *(Atriplex cinerea),* Coast Saltbush *(Atriplex isatidea)* and the tussocky grass, Beach Spinifex *(Spinifex longifolius)*. Once the initial vegetation becomes established, particularly in the offshore slopes of the foredune, perennial woody vegetation grows, eg. Coastal Daisybush *(Olearia axillaris)*, Blueberry Tree *(Myoporum insulare)*, Summer-scented wattle *(Acacia rostellifera)*, and *Tetragonia decumbens* (Eliot, not dated; Western Australian Planning Commission 2010).

Sand extraction has had a positive effect on both the migration rate and area reduction of dunes in the study area. Lancelin has five active mining leases, some of which commenced operation in the 1980s. The migration of this dune used to be fast, but has now slowed and it is inferred part of this reduction has been caused by extraction of the limesand from the leases.

The Southgate Dune will also soon have major impacts on the town of Wandina as there are only 230m between the dune and the nearest houses. To prevent further migration of the dune, extraction must be continued, allowing industry to remove the sand. The Southgate Dune has an approximate volume of 33 million $m^3$ and between 2001 and 2010 was migrating at a rate of 12.7m/year. For the purpose of volume calculations, the dune was assessed as a rectangle (Figure 42) with an average height of 4m and width of 520m at the nose of the dune. Based on these calculations, to halt the nose of the dune progressing towards the town, approximately 26,000$m^3$ of sand needs to be removed annually.

**Figure 41. Solutions to halt sand dune migration – mulch material (left-hand photo) as laid, and a vegetation succession commencing (right-hand photo) two years later.**

While the dunes at White Point and Sandy Cape have decreased in area, they have increased in migration rate, particularly during the past 10 years. Fortunately, there are several mining tenements located on both dunes which appear to have reduced the area. However, the acceleration shows that the migration rate of these dunes is influenced by other factors such as wind and sediment supply as well as surface area.

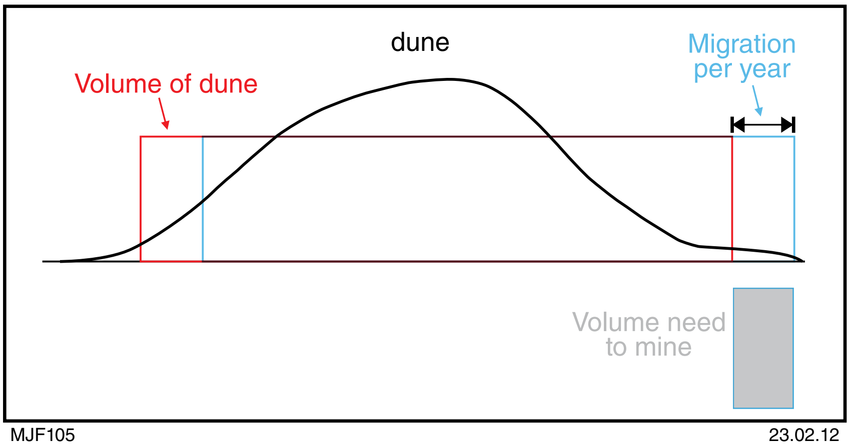



**Figure 42. Simplified calculation for the volume which needs to be extracted each year to stop Southgate Dune migration**

The limesand extraction has beneficial outcomes to reduce the dune areas and reduce migration speeds. It can also stop the dunes from impacting infrastructure, create local jobs, increase the availability of limesand for agricultural uses, ameliorate environmental impacts on farmland and it can also be used for road and other construction purposes.

The farmland soil in most parts of Western Australia is becoming increasingly acidic. To maintain farm productivity, this acidity must be neutralised by an alkaline material. Calcium carbonate in the form of crushed limestone or limesand is the preferred material. The dunes in the study area are dominantly limesand and are underlain by limestone which also constitutes the widespread relict vegetated dunes.

During the period 1995 to 2005 several attempts were made to compile a State Lime Supply Strategy by State Government authorities to provide guidance and leadership in relation to the availability of limesand and limestone in Western Australia in the face of conflicting issues of protection of native vegetation, especially in conservation lands. However, it is reported that through the complexities of the diverse geological occurrences, of the land tenure issues and of the lime usage regime, it became clear that the initial goal of a Statewide approach was not feasible.

A major component of the drive for the Lime Strategy was the inferred huge impact on the native vegetation on the coastal environments of the agriculture sector. Unfortunately, most of the limesand sites are situated in near-coastal conservation areas to which extraction could pose a threat to the natural vegetation. In addition, there is significant reluctance for freehold land owners to allow extraction, meaning that the industry is pushed onto Crown land (reserves and unallocated Crown land) to seek extraction sites.

This time also corresponded with production of the campaign “Time to Lime” by the Department of Agriculture and Food, designed to encourage farmers to add alkaline limesand to their acidifying soils. The campaign was an overall success and lime usage in agriculture has increased over the past 10 years.

The near-shore limesand contains minor but significant levels of common salt, (sodium chloride), derived from sea spray that can infiltrate the soil and ground water systems, elevating salinity. The quantity of limesand required for agricultural purposes is determined by the percentage of calcium carbonate. As limesand has different neutralising values, the higher the percentage of calcium carbonate in the limesand, the less volume is required for the same pH change in the soil (Environmental Protection Authority 2007). The salt content is not normally considered but needs to be identified as a potential issue if the lime addition rates rise.

# Conclusions

The mobile sand dunes in the study area consist of fragmented biogenic material such as bryozoa, mollusc, foraminifer and calcareous algae that originated offshore. The organic lime material is pulverised to sand-sized particles by wave action, transported to the shore, built up on the beach and into foredunes, from where it can be blown as dunes inland. Former terrestrial sand dunes that became cemented into limestone have been submerged through subsequent transgressions and have formed a series of offshore reefs located 2-10km west of the present shoreline. These have become additional sources of limesand through submarine erosion.

The sheltered location created by the reef produced a micro-tidal range and low wave-energy environment that has helped in the development of the sandy beaches. The beach sand is blown to form frontal dunes which, over time, become colonised with vegetation and the dunes then become stabilised. However, natural processes, including fires and drought, and more recently human activity and animal grazing, have all contributed to the subsequent removal of any foredune vegetation cover. Bare sand surfaces allow for the potential destabilisation of the foredune and any adjacent shore-parallel dune ridges that may have developed. Strong onshore winds are then able to erode gaps in the dune ridges and cause blowouts which then migrate as mobile parabolic dunes.

The morphology of a coastal sand dune is influenced by the wind, vegetation and the shape, outline and overall morphology and nature of the coast itself.

Parabolic dunes initiated by blowouts occur when the crest of the dune advances rapidly while the limbs are held back by vegetation, resulting in the trailing arms becoming longer during the migration of the dune. In situations where the vegetation cover over trailing arms is removed, extensive transgressive sand sheets such as Cape Burney-Southgate, Wedge Island East and Lancelin develop.

The wind along the west coast of Australia – the dominant factor governing dune migration – is controlled by competing, large scale, seasonal weather systems. Within the study area, all dunes are migrating northerly rather than inland to the east due to the strong shore-parallel southerly winds. Variation in the trend of the coastline and the wind regime results in the migration directions (Figure 13) of the dunes varying in such a way that the southern-most dunes are migrating north-northwesterly, dunes in the central part of the study area migrate mainly northerly to north-northeasterly, and the most northerly dunes are moving northerly to north-northwesterly.

The strong southerly sea breeze has wind velocities of 20-40km/h and occurs mostly in summer between 2pm and 8pm. Precipitation is lower in summer than winter and temperatures are higher. Therefore, the prime mobilisation period of dunes is mainly in summer. The analysis conducted in this study indicates that the highest migration period was during Period 3 (2001–10) which had lower precipitation levels than Period 2 (1982–2001) and Period 1 (1960–82). It is noticeable that there were two years of abnormally high temperatures in 2003 and 2006 which are correlated with two strong El Nino events in Period 3 when migration rates in general were high.

The correlation between the migration rate and the size of the dune demonstrates that the larger the dune, the faster they migrate. During the past 50 years, the dunes decreased in size with some shrinking over 60 per cent, eg. Cape Burney and Dongara East. Within the study area only the Illawong and Green Head South dunes increased in size. Illawong increased by 11 per cent which was due to the availability of a strong sediment supply. In comparison, Green Head South only increased by 3 per cent. However, this dune, which is now severed from its beach sand supply, no longer has a connection with a beach sediment supply to account for this increase.

Stabilisation of the mobile dunes is extremely important to prevent the dunes becoming geohazards. The dune migration in this study area is a slow and pervasive geomorphologic event which will cause major material and socio-economic damage. As such, mitigating the migration impacts by introducing vegetation cover or extraction and marketing of limesand should be a high priority for all the dunes that are or have potential to become a geohazard over the next few years.

Prime threats to infrastructure occur at the following sites:

- Kailis Drive, which is currently in the migration path of the Dongara West Dune
- The recently opened Indian Ocean Drive which the Grey Dune is approaching
- The very popular scenic tourist route north of the Green Head town, only 42m from the closest dune which has been calculated as migrating at a rate of 17.1m per year

It is recommended that the migration of the mobile sand dunes in the study area be addressed, including assessment of options to prevent the development of future geohazards caused by additional mobile sand dunes commencing from the parallel dune ridges.

To slow the migration of mobile sand dunes, the roughness density needs to be increased. This will decrease the wind speed and therefore the saltation flux. Methods to increase the roughness density include the construction of fences across the path of the prevailing wind, planting local vegetation in a checkerboard pattern and covering the surface of the dune with wood chips, pruning material and straw which need to be crimped to the surface. Government has already taken steps to stop part of Grey Dune from impacting the Indian Ocean Drive by removing limesand adjacent to the highway and covering the surface with stockpiled topsoil and mulch material to allow plants to grow on the remaining sand and ultimately create a vegetation succession (although future impacts in a new part of the highway are predicted). It is hoped that the vegetation cover will stabilise the dune, resulting in the prevention of accidents, delays and economic loss caused by the mobile sand dune adjacent to the treated area.

Mining leases in the study area can play an important role in halting mobile sand dunes where extraction is undertaken. The mechanical excavation of the limesand can reduce the size of the dune, remove sand ahead of the dune and can cut dunes off from sediment supply. The extracted limesand can then be used for road construction and for neutralising acidic soil in the agricultural farmlands of the wheatbelt. However, it is important that only limesand with a high percentage of calcium carbonate can be used in agriculture soil neutralisation because of increased costs from transporting larger quantities of lower grade limesand. Additionally, any increase in the salt levels of modern limesand from the nearshore environment can negatively impact the groundwater underlying farmlands.

While various methods can be implemented to halt and slow down the migration of mobile sand dunes, it is more important to prevent the development of geohazardous mobile dunes in the first place by educating people about the potential geohazards. This increased awareness should have a decisive impact on how mobile sand dunes and potentially mobile dunes are handled and treated in the future. It is also important that parallel beach ridges be protected by the use of signage, artificial walkways and the prohibition of driving vehicles within the threatened dunes. These safety measures will decrease the destruction of the vegetation cover which will in turn prevent blowouts. Without blowouts the sediments will stay on the beach and cannot easily form a mobile sand dune.

# Acknowledgements

The work by first author Josefine Bruch was carried out while on an educational student exchange program (International Association for the Exchange of Students for Technical Experience – IASTE) supported by the Department of Mines and Petroleum (DMP) in Western Australia.

Josefine thanks her supervisor, Mike Freeman from DMP, for his support, guidance and mentoring during the exchange; Ivor Roberts and IASTE for the opportunity to undertake a three-month internship at DMP; Bob Gozzard for his advice on ArcGIS and for providing data, assistance and taking part in many constructive discussions; Sean Doherty for he help with ArcGIS and graphics. Additional data was supplied by the Bureau of Meteorology and many of the images were compiled through using Google Earth.

Finally Josefine would like to thank her family for their unconditional support and guidance along the way.

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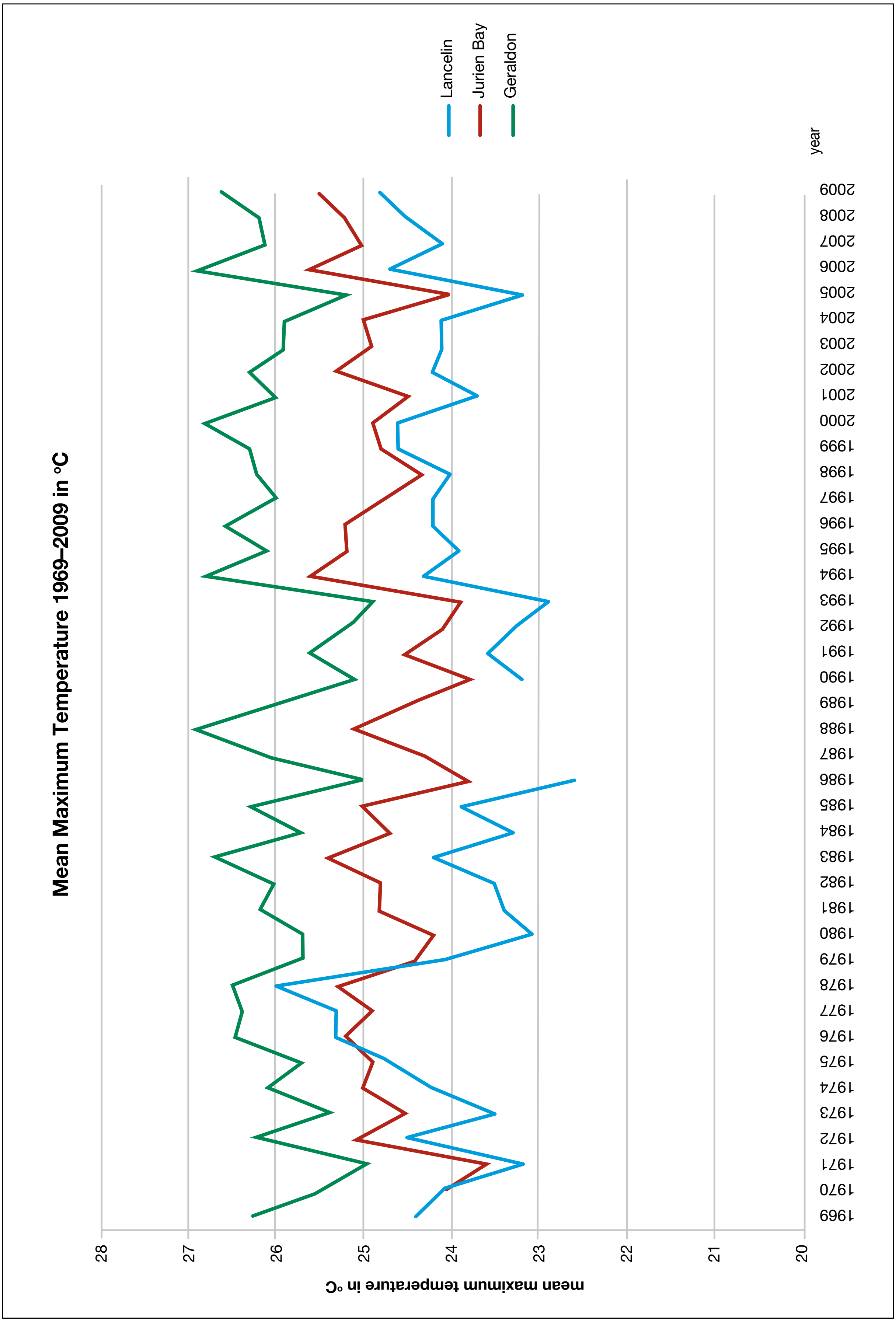
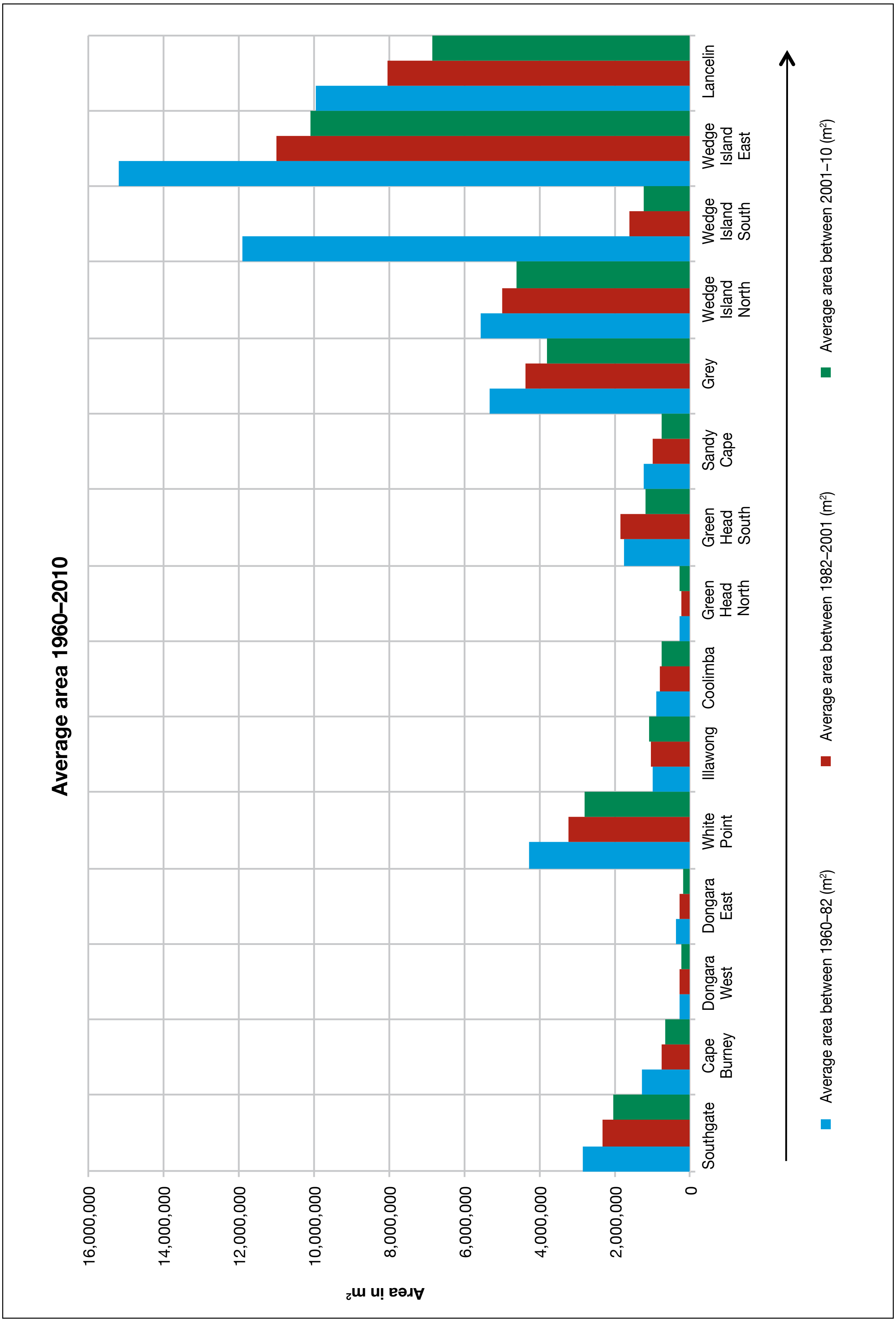
# APPENDICES

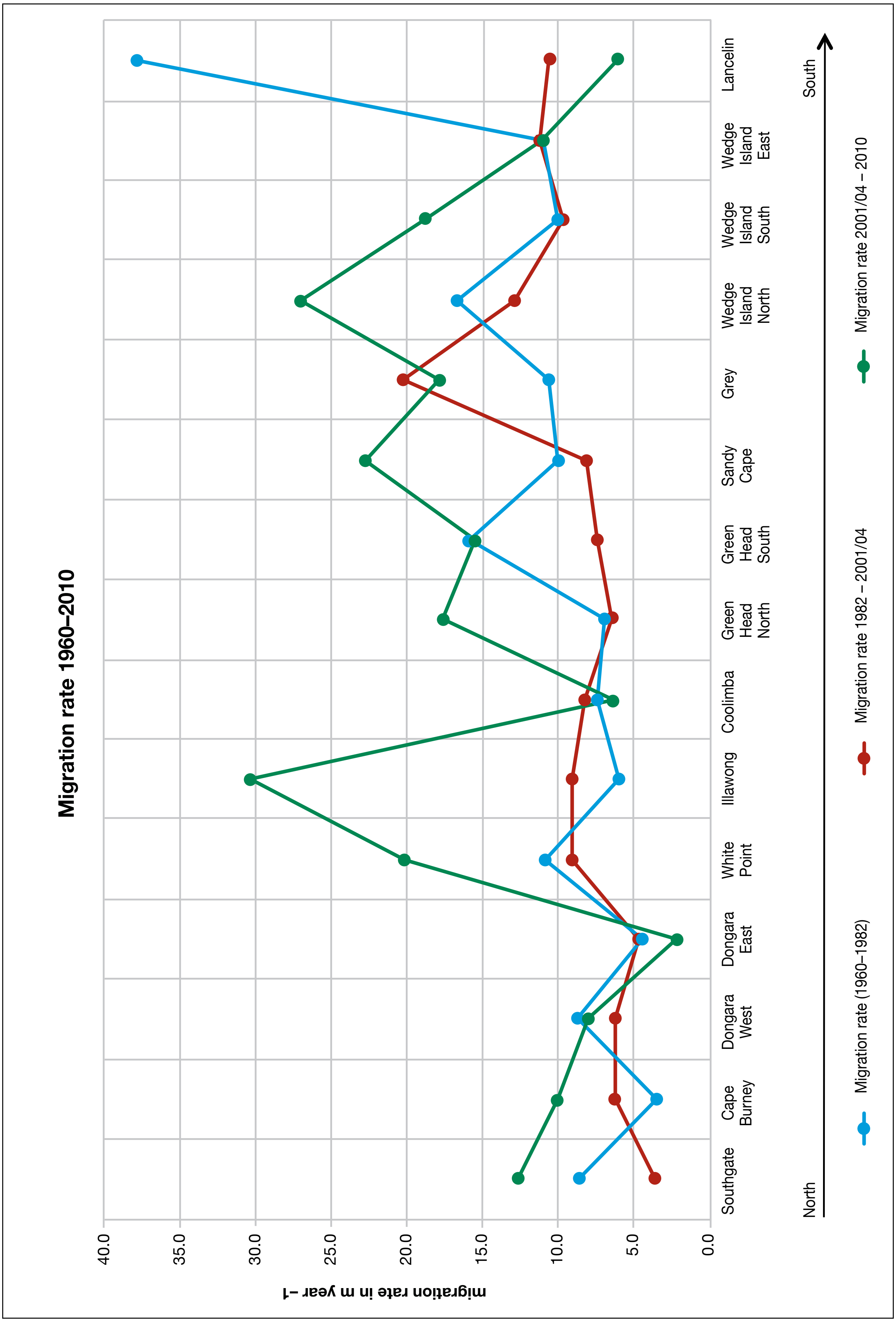
# APPENDIX A. Temperature data from 1969–2009



# APPENDIX B. Average areas of dunes in three measured periods

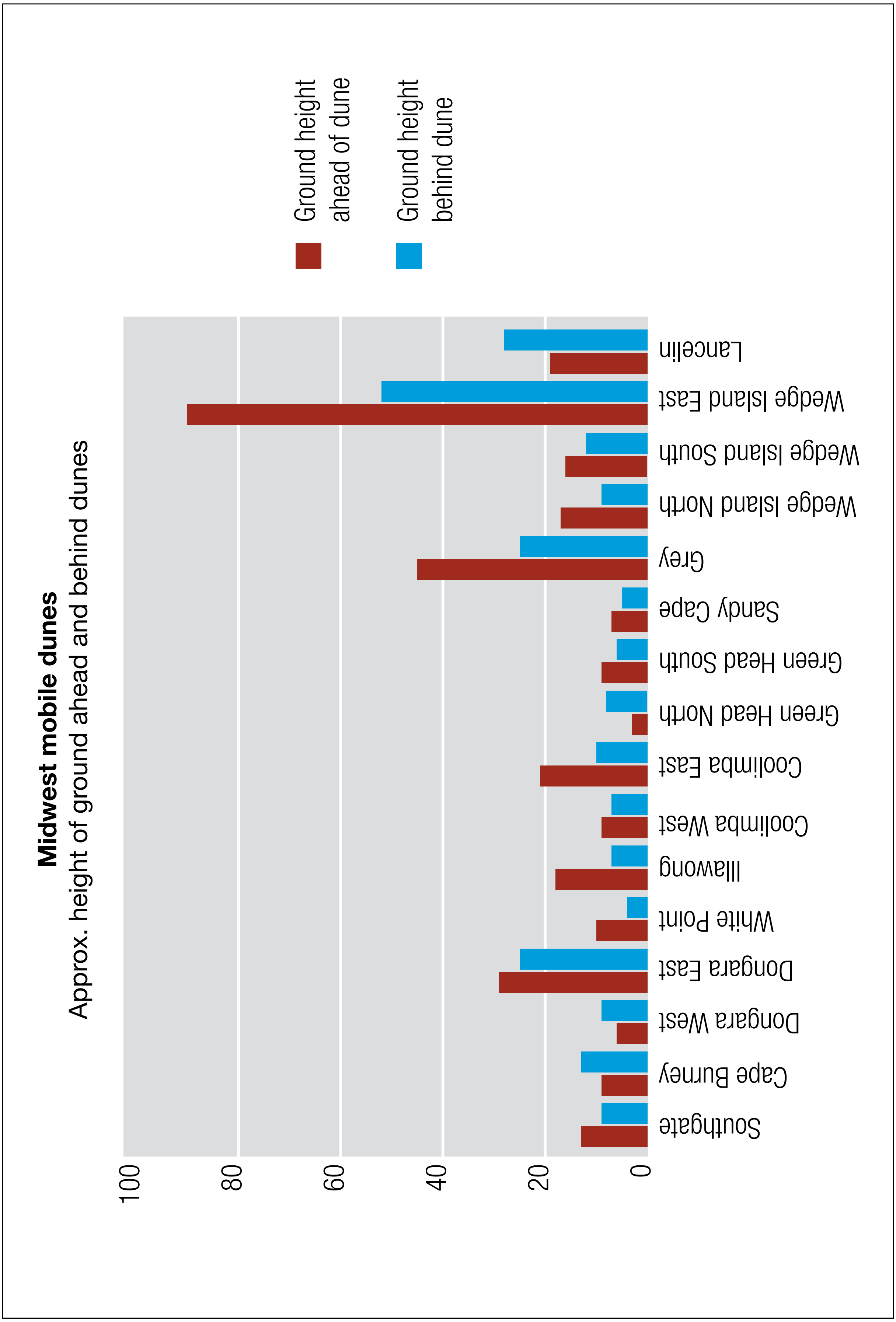


# APPENDIX C. Migration rate 1960–2010



## APPENDIX D. Graph showing relative heights of dunes ahead and behind each.

Note the Wedge Island East is anomalous



## APPENDIX E. Sand areas and volume estimates on tenements related to dunes. Tenement data as at 6/10/2016

| Dunes | Area (m²) | Volume (m³) | Migration rate (m year-1) | Tenements*[8] | Status of tenement (#) | Holder/Applicant |
|---|---|---|---|---|---|---|
| Southgate | 1 937 807 | 35 410 078 | 6.8 | See footnote [9] | – | – |
| Cape Burney | 600 049 | 17 953 634 | 5.4 | – | – | – |
| Dongara West | 202 239 | 1 496 578 | 7.7 | M70/311 | Live (25/7/1988) | Cockburn Cement Ltd |
| | | | | M70/1271 | Live (10/12/2015) | Westdeen Holdings Pty Ltd |
| | | | | E70/355 | Live (24/7/1987) | Cockburn Cement Ltd |
| | | | | E70/4634 | Pending (7/10/2014) | Bulkwest Pty Ltd |
| Dongara East | 137 087 | 4 218 115 | 4.1 | See footnote [9] | – | – |
| | | | | M70/1343 | Pending (20/7/2015) | Ian West |
| White Point | 2 548 702 | 15 923 192 | 11.9 | M70/642 | Live (10/6/1996) | Cockburn Cement Ltd |
| | | | | M70/711 | Live (26/5/1992) | Cockburn Cement Ltd |
| | | | | E70/1721 | Pending (5/8/1996) | Cockburn Cement Ltd |
| Illawong | 1 119 343 | 8 566 898 | 9.4 | E70/2221 | Pending (8/7/1999) | Goldgate Holdings Pty Ltd |
| Coolimba | 714 217 | 4 472 435 | 7.7 | M70/1357 | Pending (9/9/2016) | Minawaha Farms Pty Ltd |
| | | | | M70/932 | Live (26/11/1997) | Minawaha Farms Pty Ltd |
| Green Head North | 286 532 | 1 353 573 | 8.5 | P70/1468 | Live (9/2/2007) | Minawaha Farms Pty Ltd |
| Green Head South | 1 743 305 | 13 061 003 | 12.5 | M70/782 | Live (4/2/1997) | Minawaha Farms Pty Ltd |
| | | | | M70/1066 | Live (9/8/2013) | Westdeen Holdings Pty Ltd |
| | | | | M70/1667 | Pending (7/11/2014) | Westdeen Holdings Pty Ltd |
| Sandy Cape | 714 878 | 3 396 742 | 11.3 | – | – | – |
| Grey | 3 783 873 | 147 723 565 | 15.7 | – | – | – |
| Wedge Island North | 4 632 569 | 34 250 703 | 15.8 | M70/1321 | Pending (2/1/2014) | Mineral Sand Mining and Development Pty Ltd |
| | | | | M70/1150 | Pending (3/6/2003) | Mineral Sand Mining and Development Pty Ltd |
| | | | | M70/1144 | Pending (5/5/2003) | Mineral Sand Mining and Development Pty. Ltd |
| Wedge Island South | 1 132 415 | 16 016 247 | 10.6 | M70/1144 | Pending (5/5/2003) | Mineral Sand Mining and Development Pty. Ltd |
| Wedge Island East | 10 058 170 | 832 504 959 | 11.2 | E70/1542 | Live (23/12/2010) | Enmic Pty Ltd |
| | | | | E70/4488 | Pending (12/4/2013) | Mineral Sand Mining and Development Pty. Ltd |
| Lancelin | 6 744 495 | 100 392 703 | 22.8 | M70/54 | Live (28/11/1983) | Lavar Pty Ltd |
| | | | | M70/249 | Live (7/10/1986) | Westdeen Holdings Pty Ltd |
| | | | | M70/250 | Live (20/10/1986) | Westdeen Holdings Pty Ltd |
| | | | | M 70/692 | Live (29/10/1991) | Westdeen Holdings Pty Ltd |
| | | | | M 70/994 | Pending (15/10/1997) | Enmic Pty Ltd |

[8] *M = Mining Lease *E = Exploration License *P = Prospecting License # Date of application for pending tenement or of grant for live tenement

[9] Note. Part is on freehold land and therefore extraction is proceeding by authority of Local Government Authority

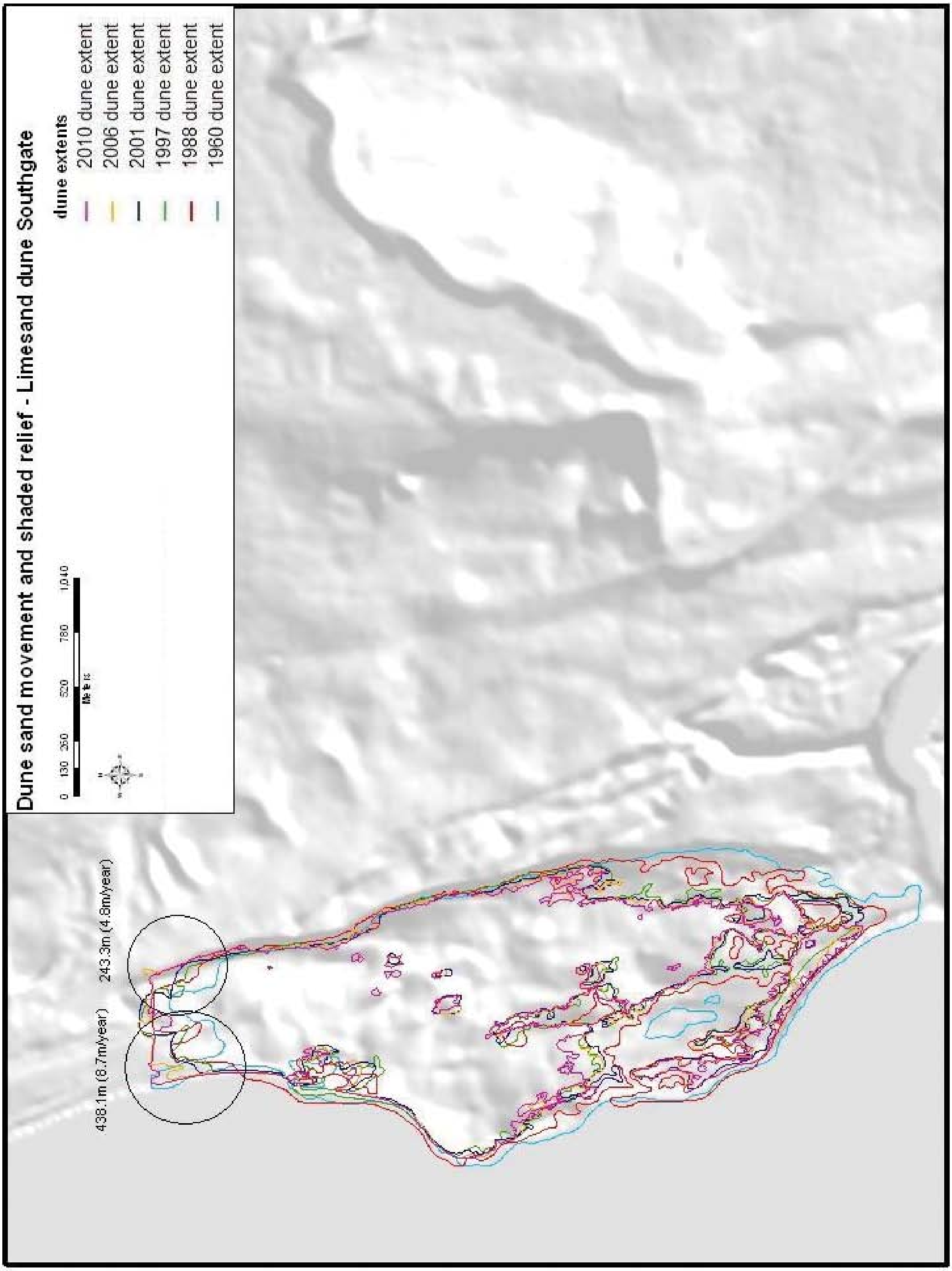
# APPENDIX F.

## Dune areas analysed in study showing boundaries of areas used for calculation and geomorphology of each dune and surroundings

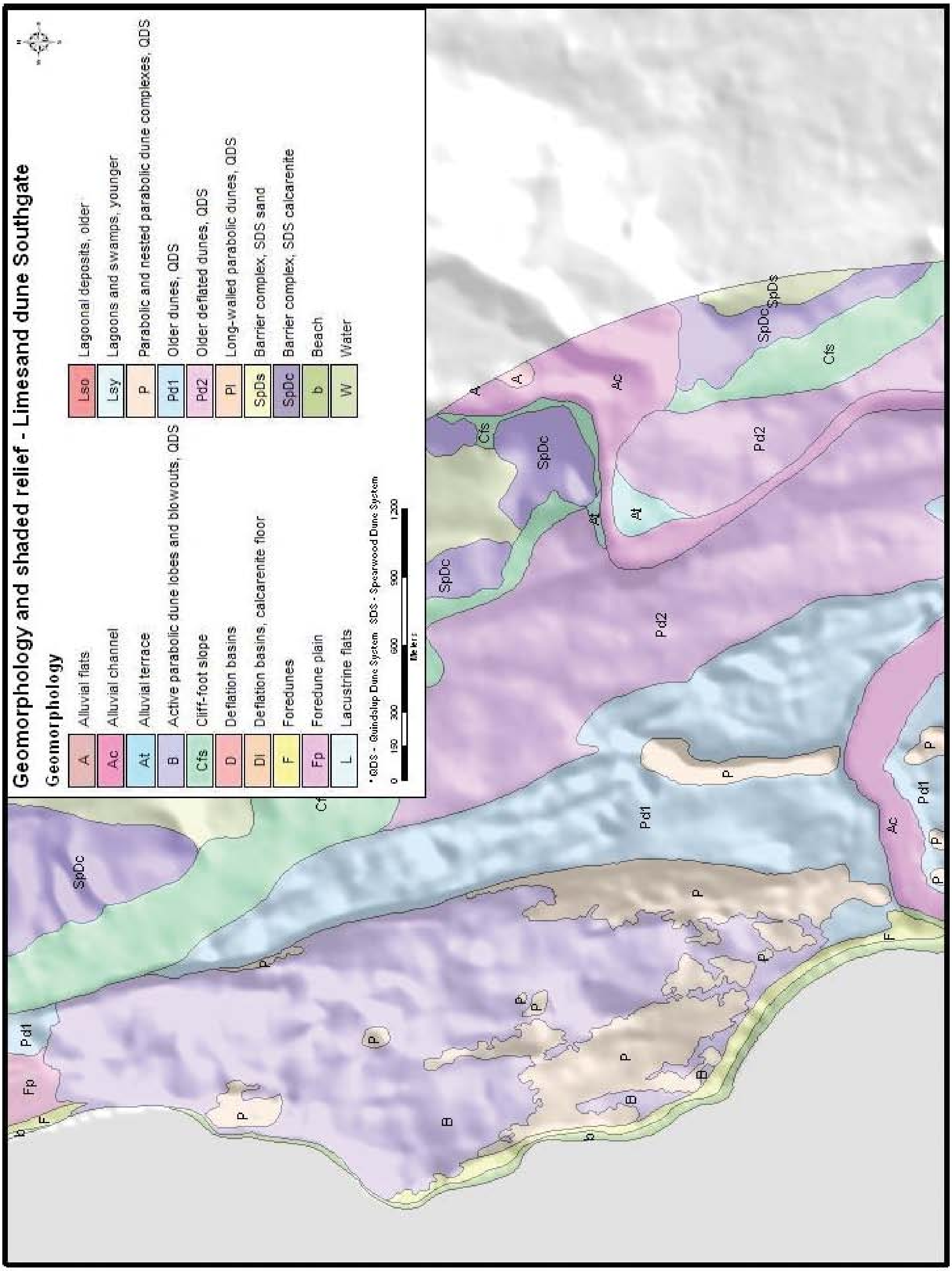
NOTES

1. The circles on the mobile sand dunes show sites of measurements.
2. The movement of the dune heads within each circle defines the direction of movement; and
3. They are listed in sequence from north to south in the study area.

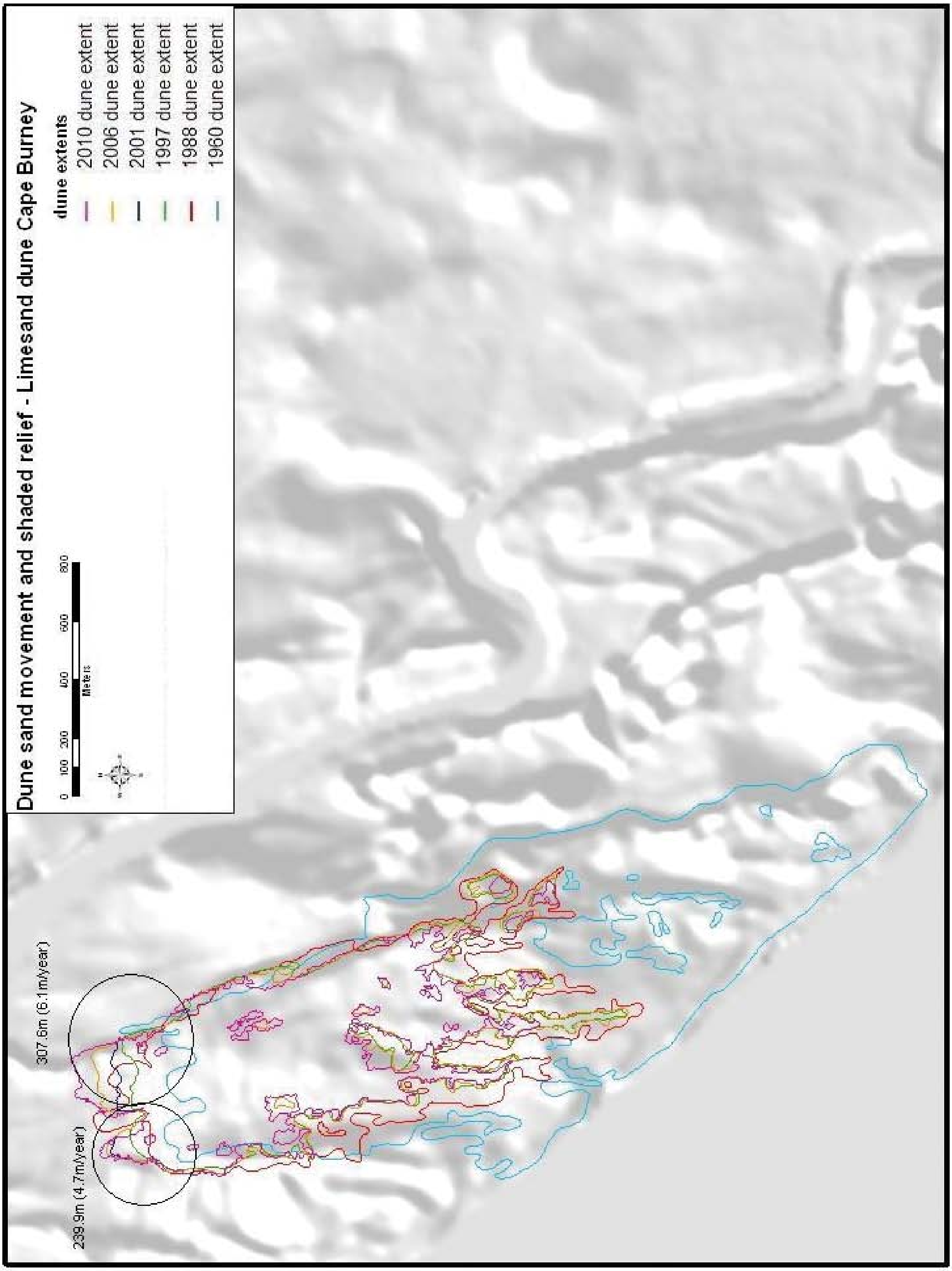
## Limesand dune Southgate – Migration



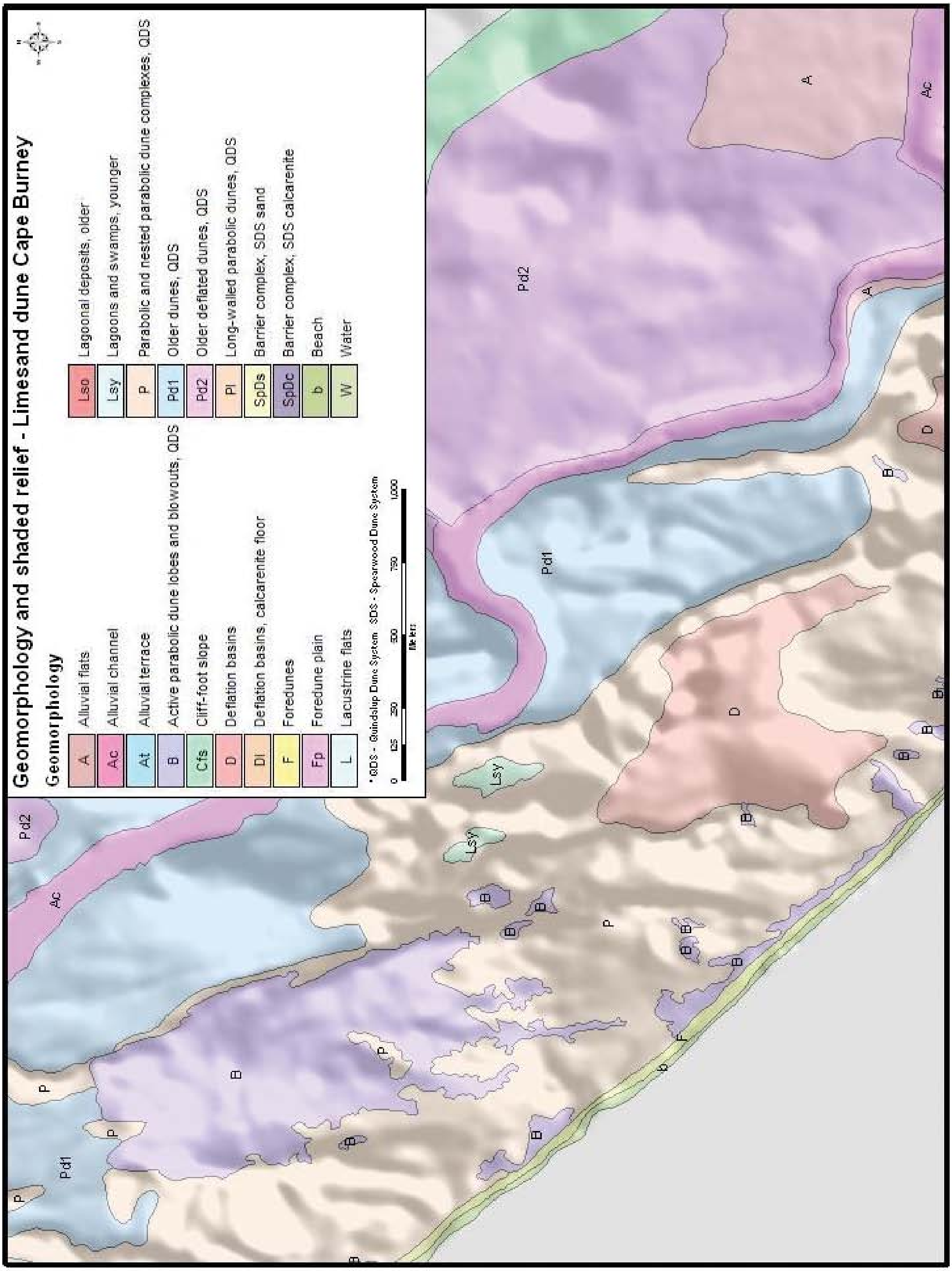
## Limesand dune Southgate – Geomorphology



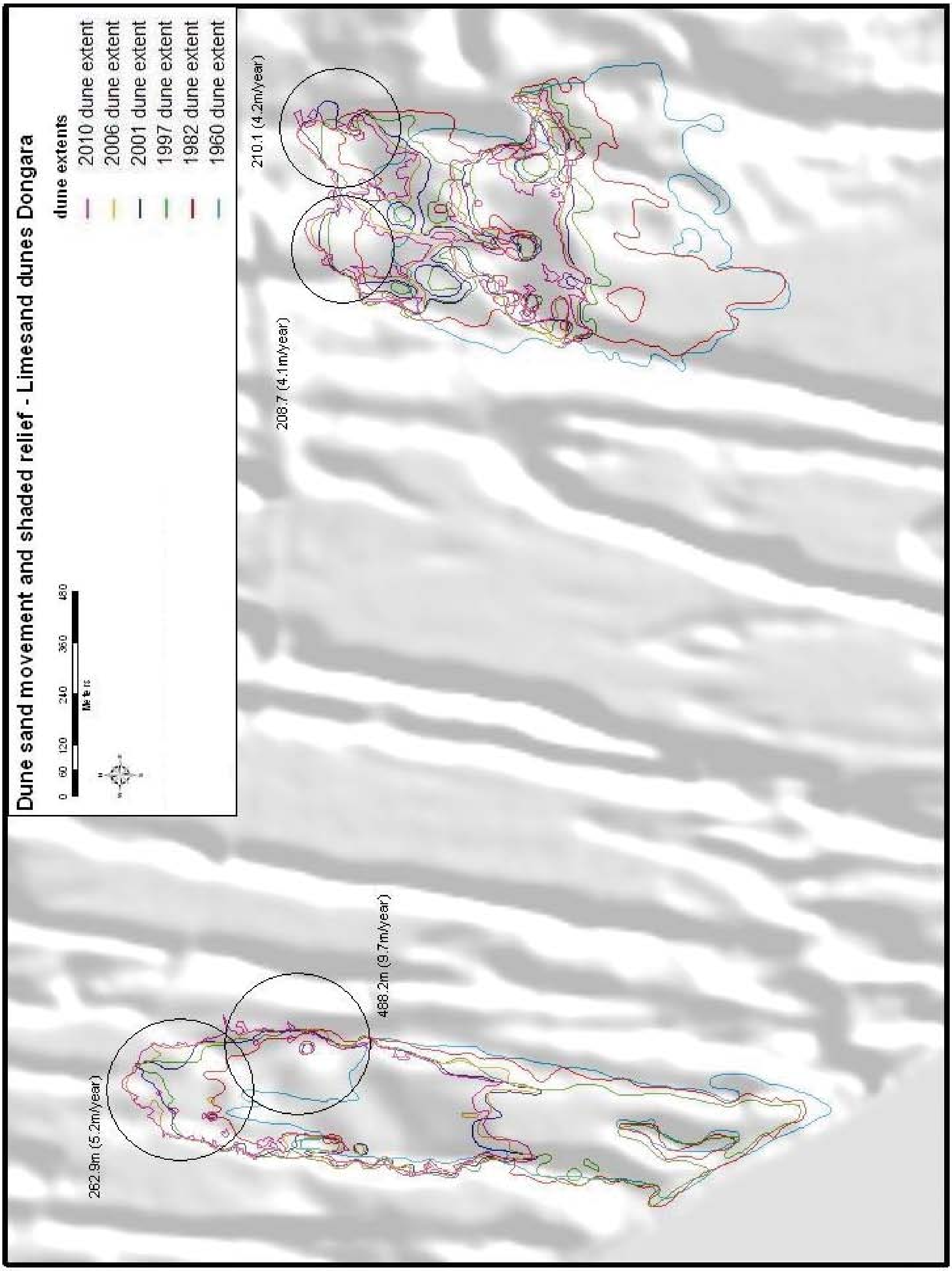
## Limesand dune Cape Burney – Migration



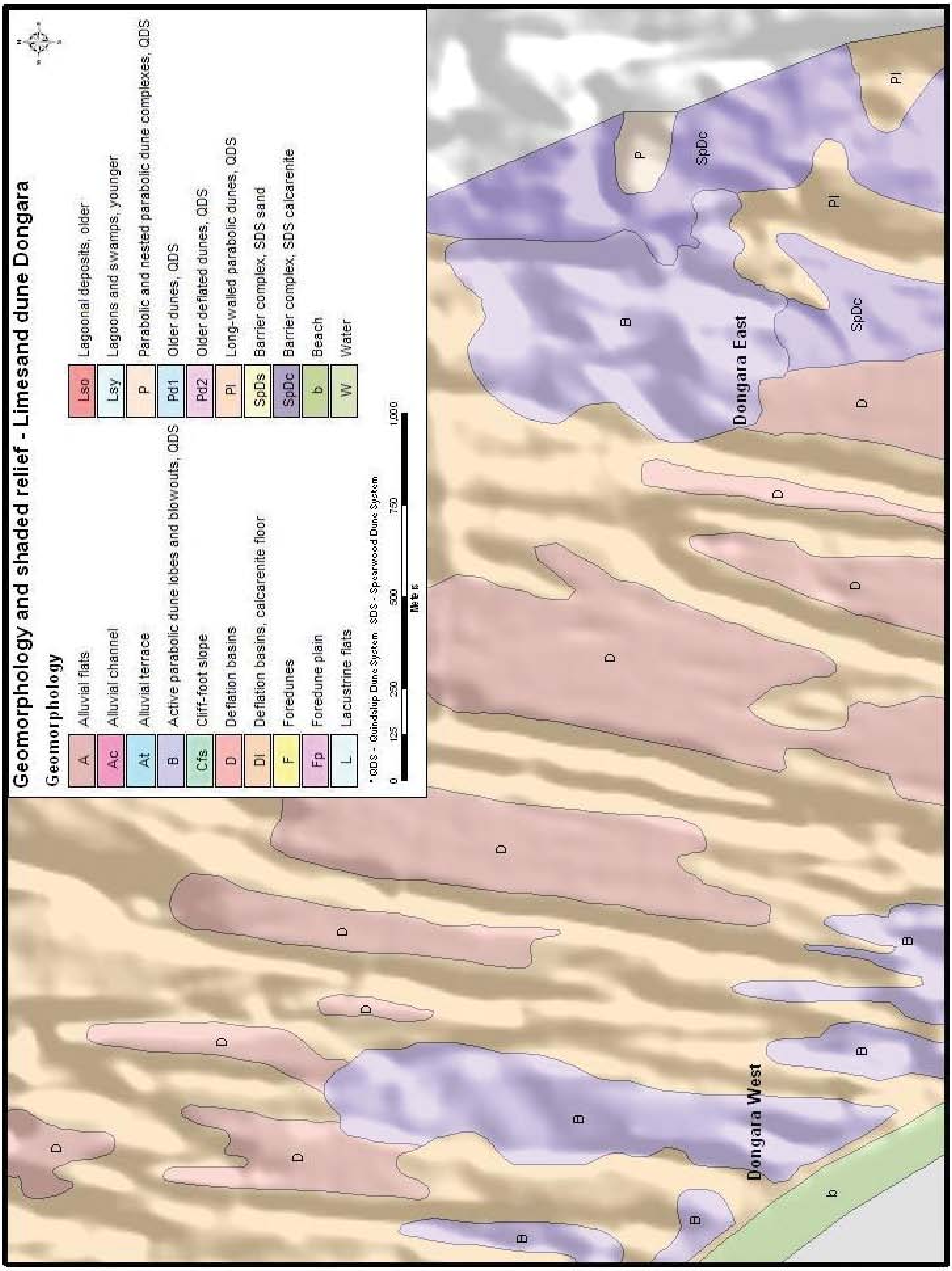
## Limesand dunes Cape Burney – Geomorphology



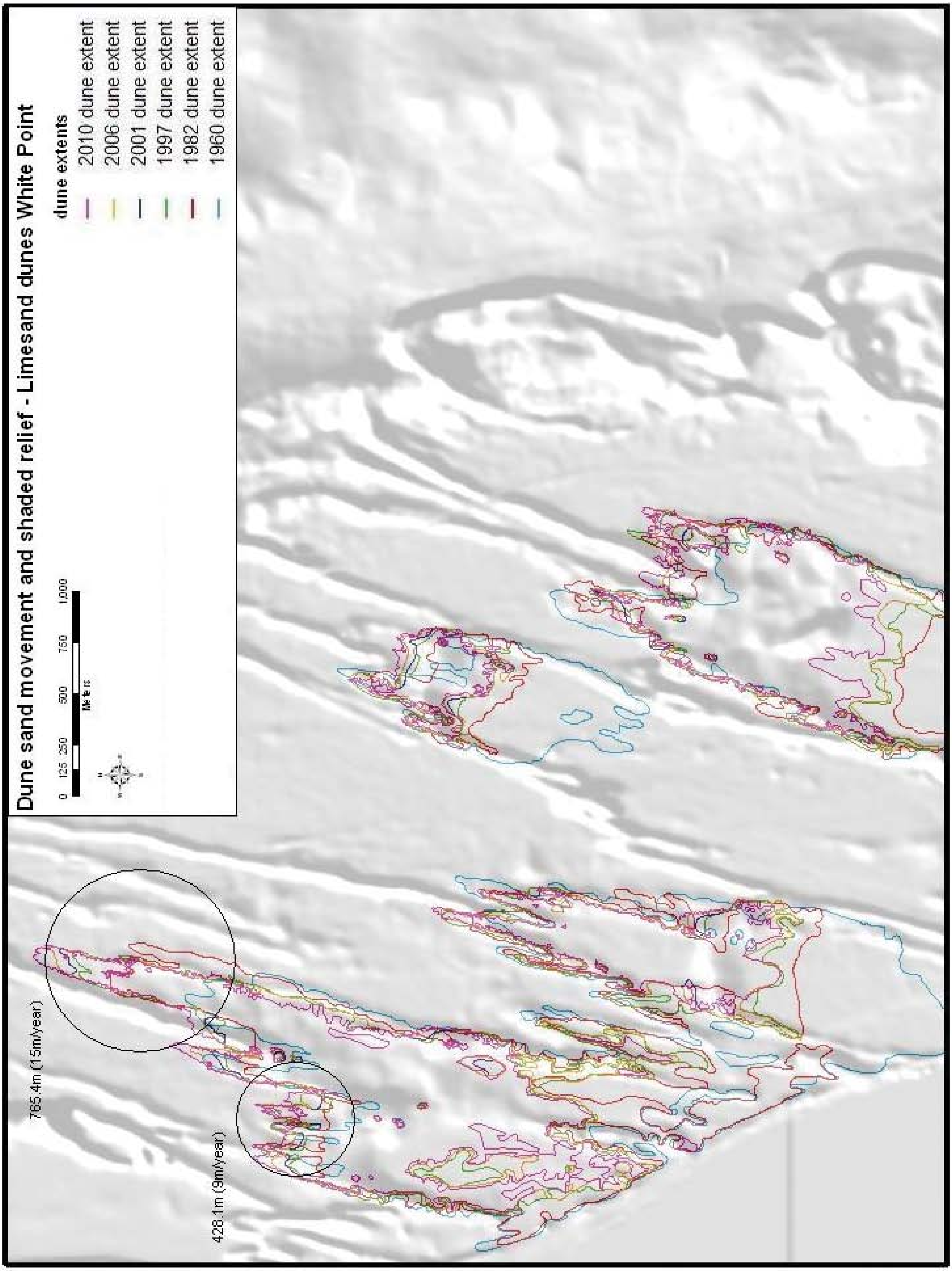
## Limesand dunes Dongara – Migration



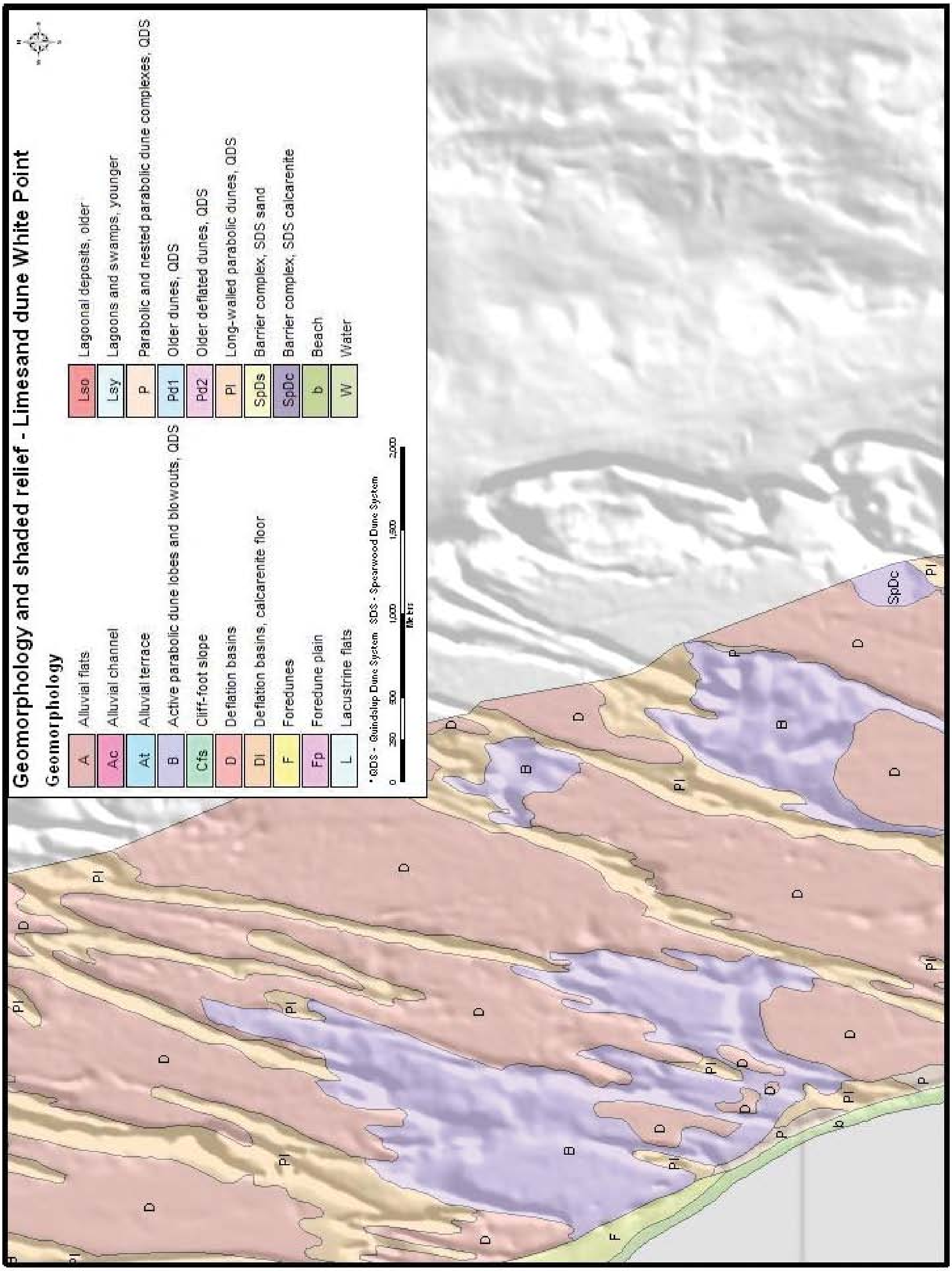
## Limesand dunes Dongara – Geomorphology



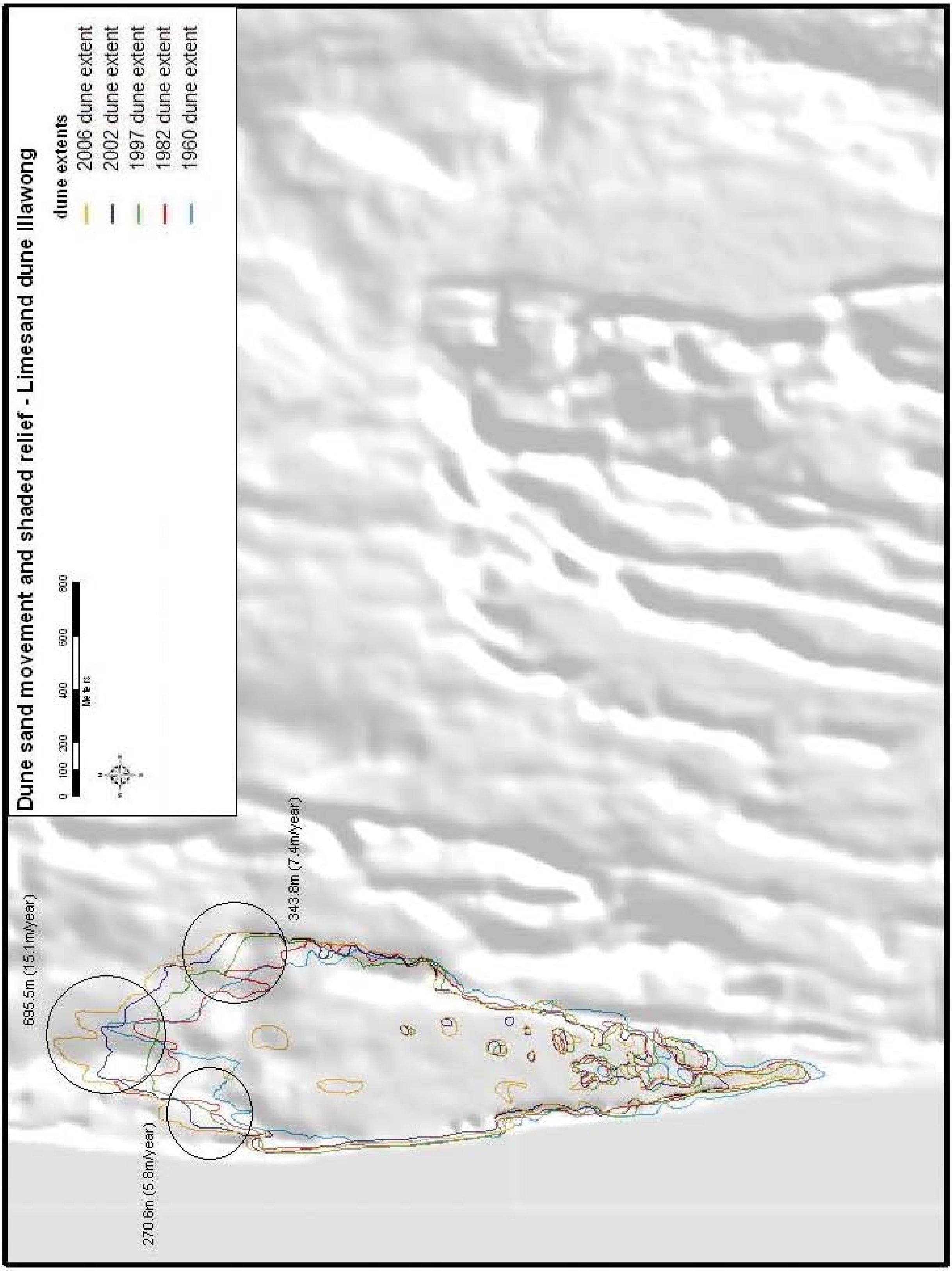
## Limesand dunes White Point – Migration



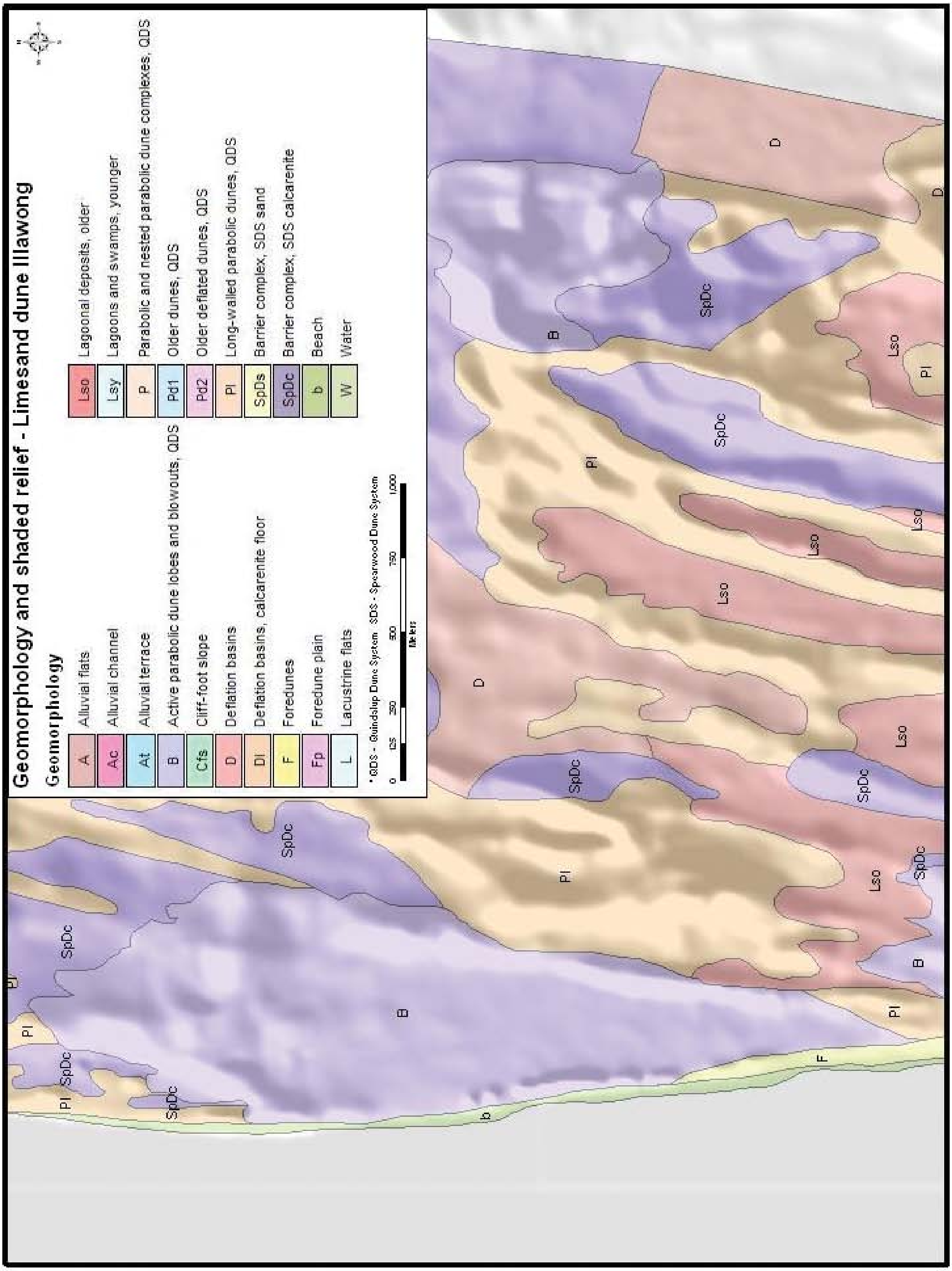
## Limesand dunes White Point – Geomorphology



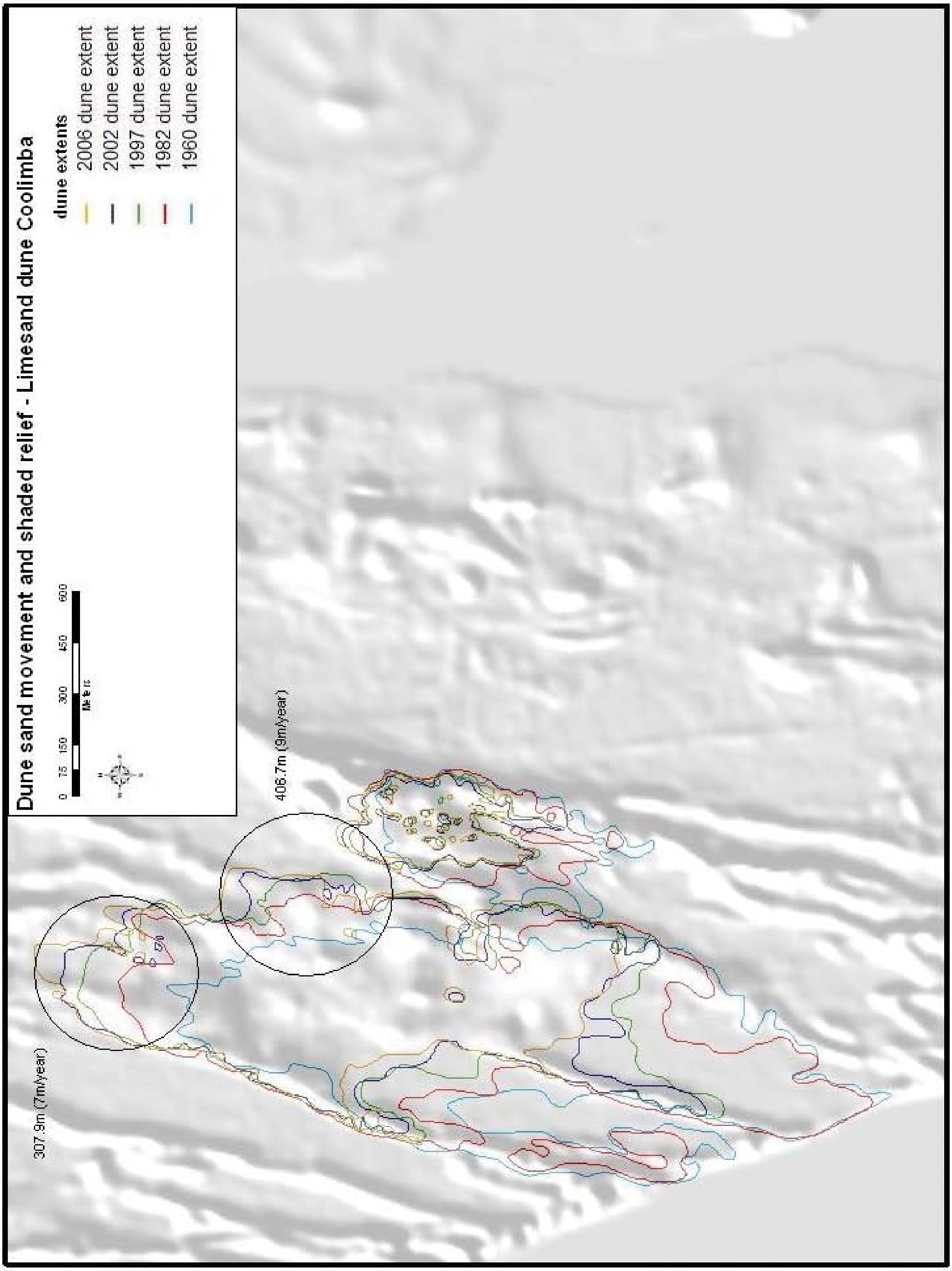
## Limesand dune Illawong – Migration



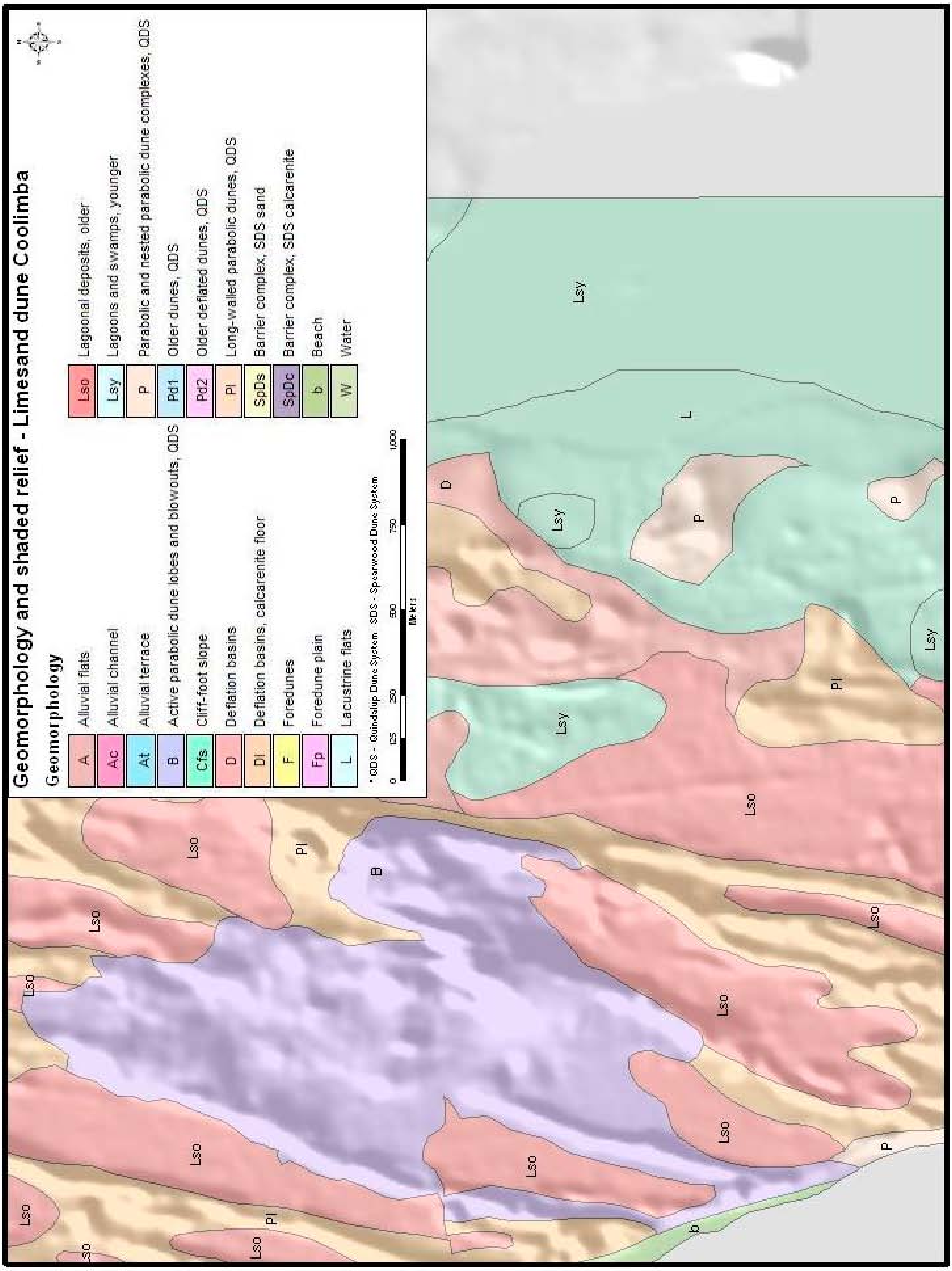
## Limesand dune Illawong – Geomorphology



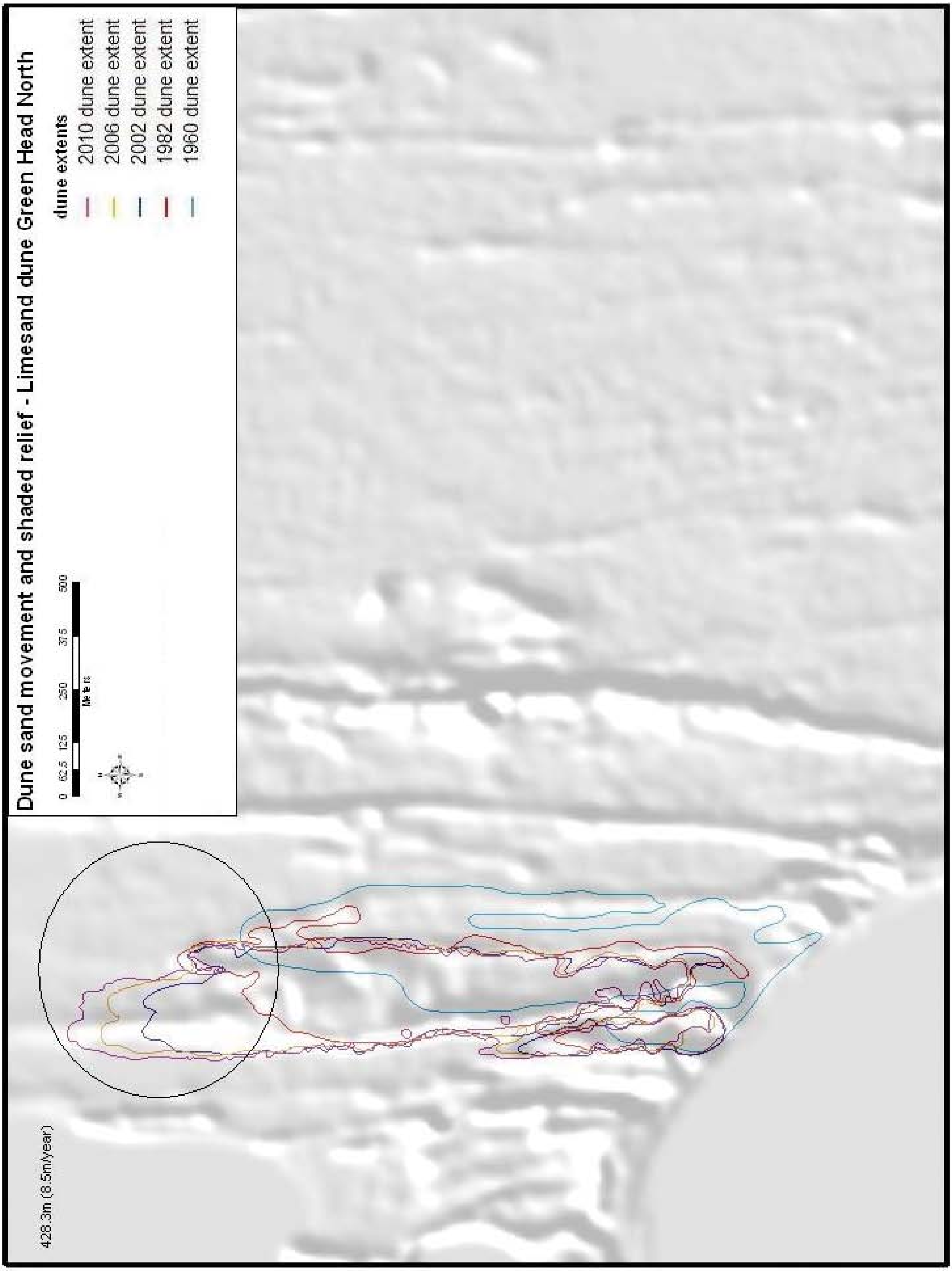
## Limesand dune Coolimba – Migration



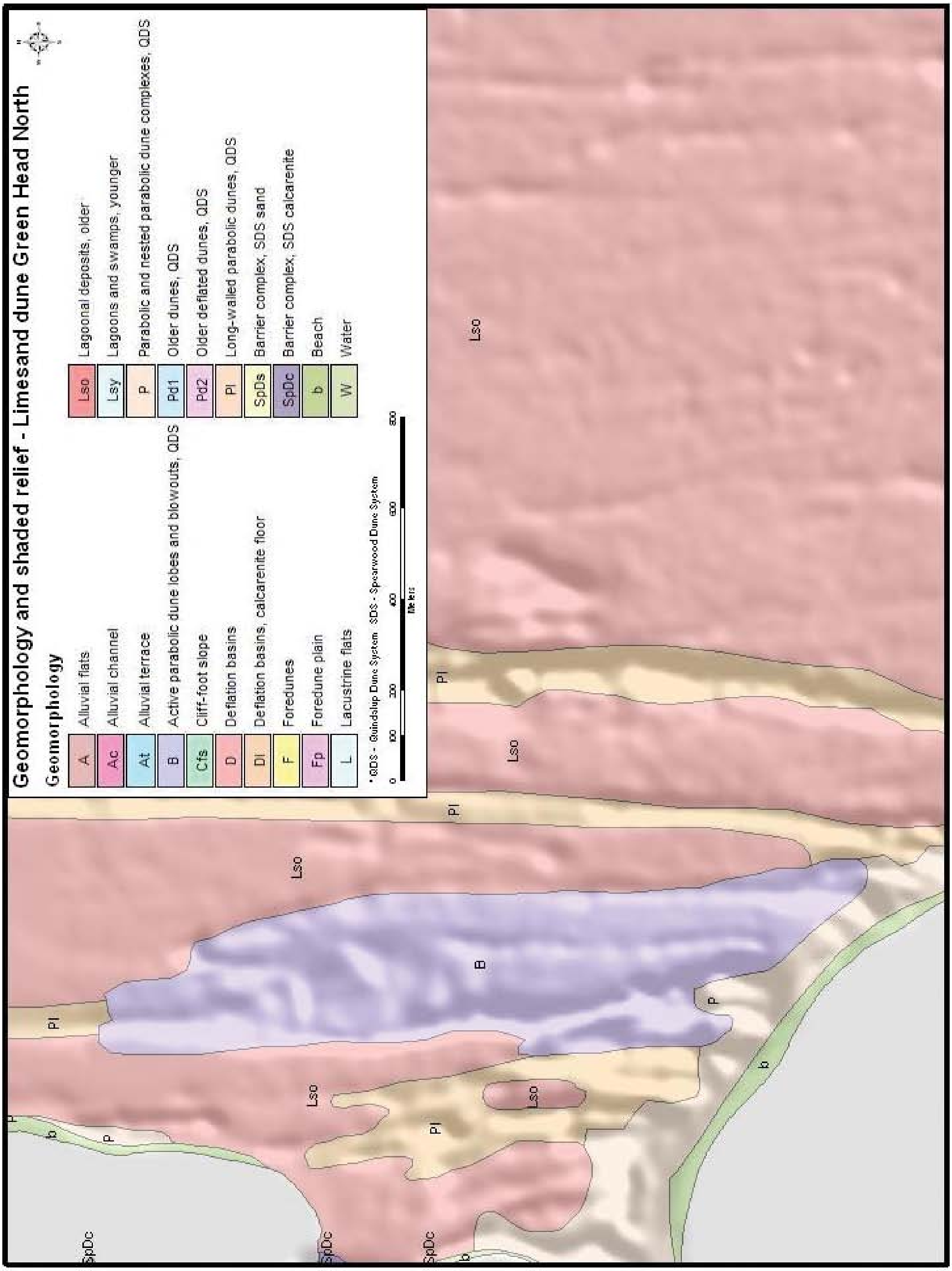
## Limesand dune Coolimba – Geomorphology



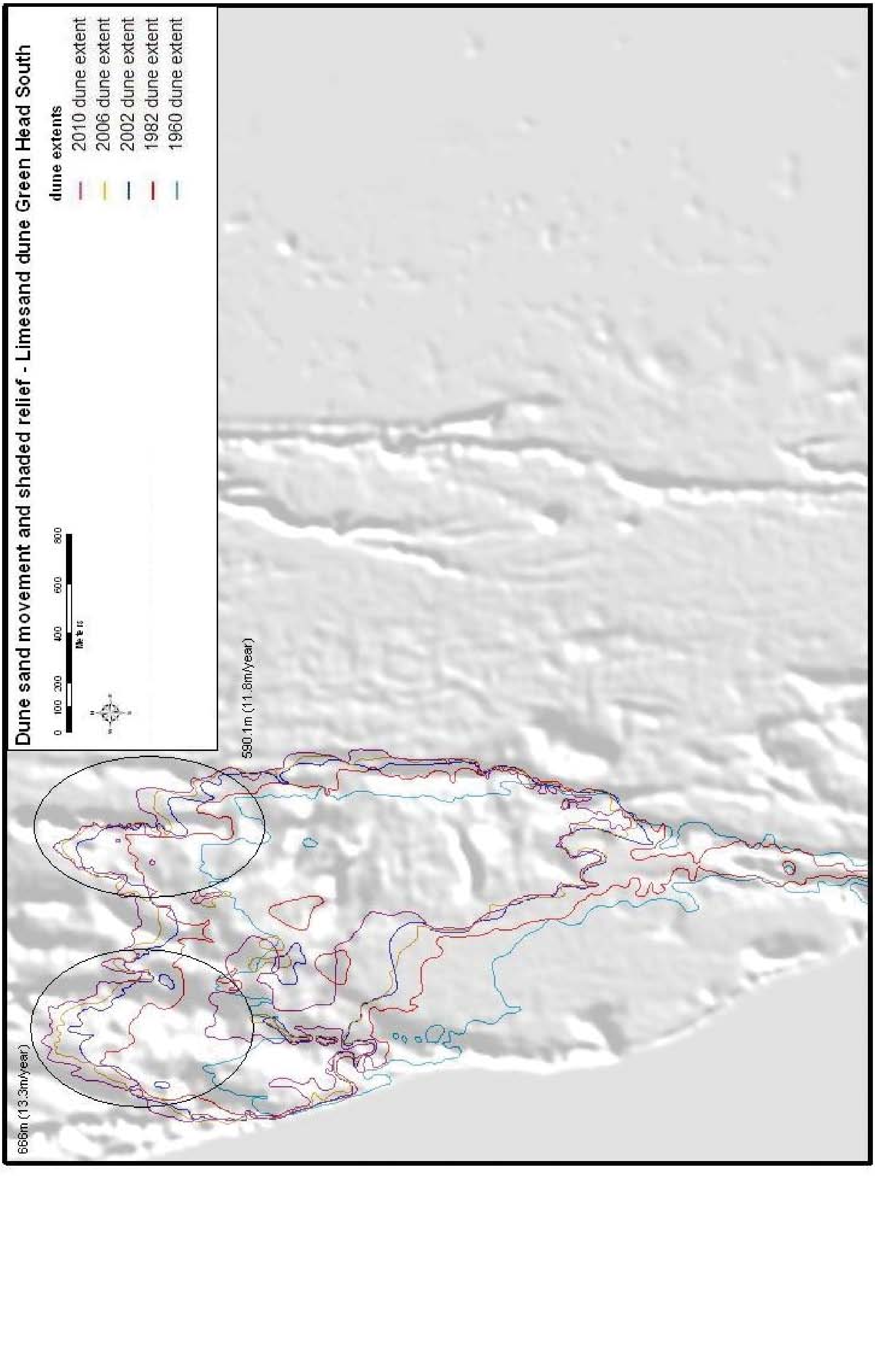
## Limesand dune Green Head North – Migration



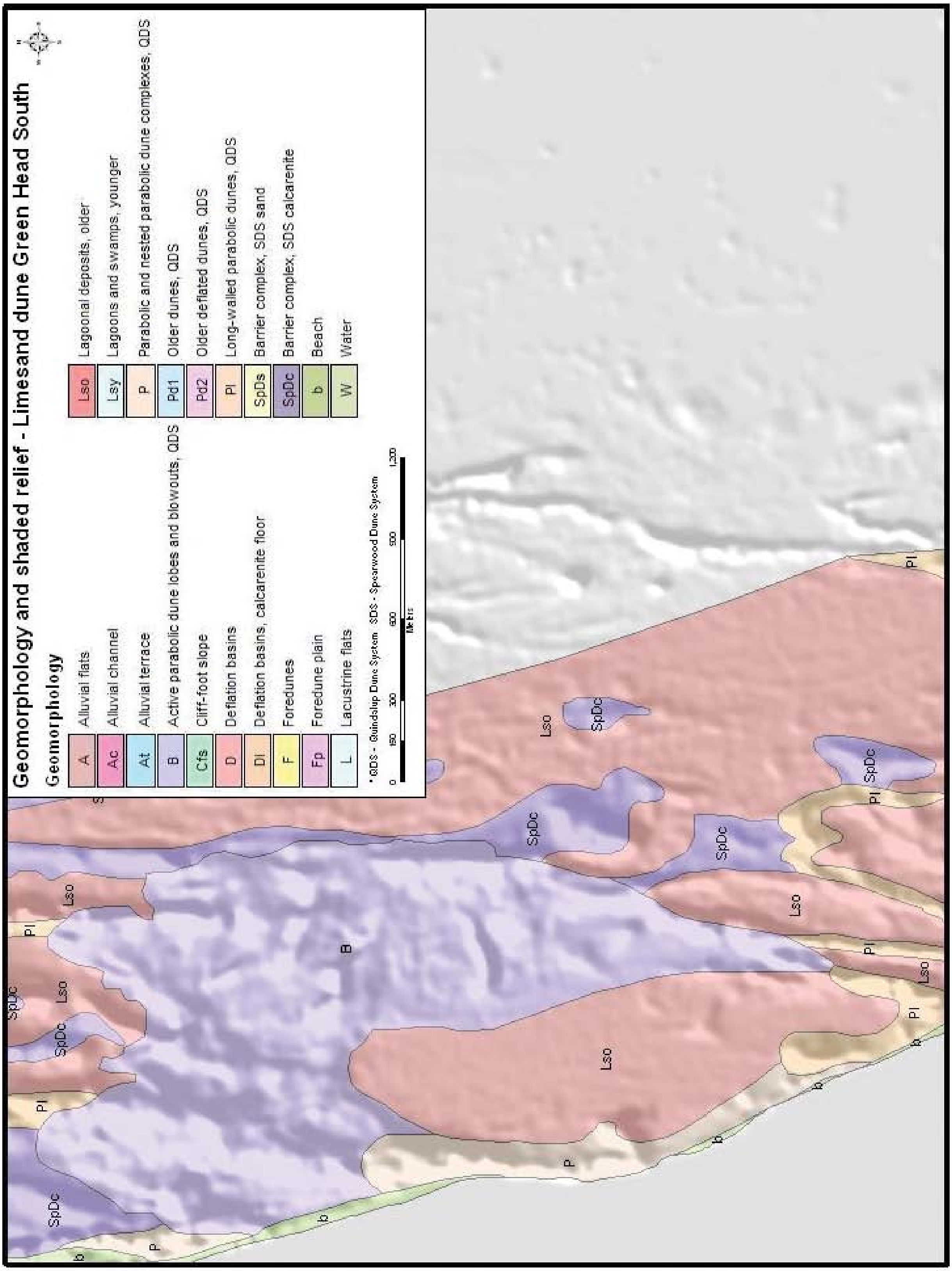
## Limesand dune Green Head North – Geomorphology



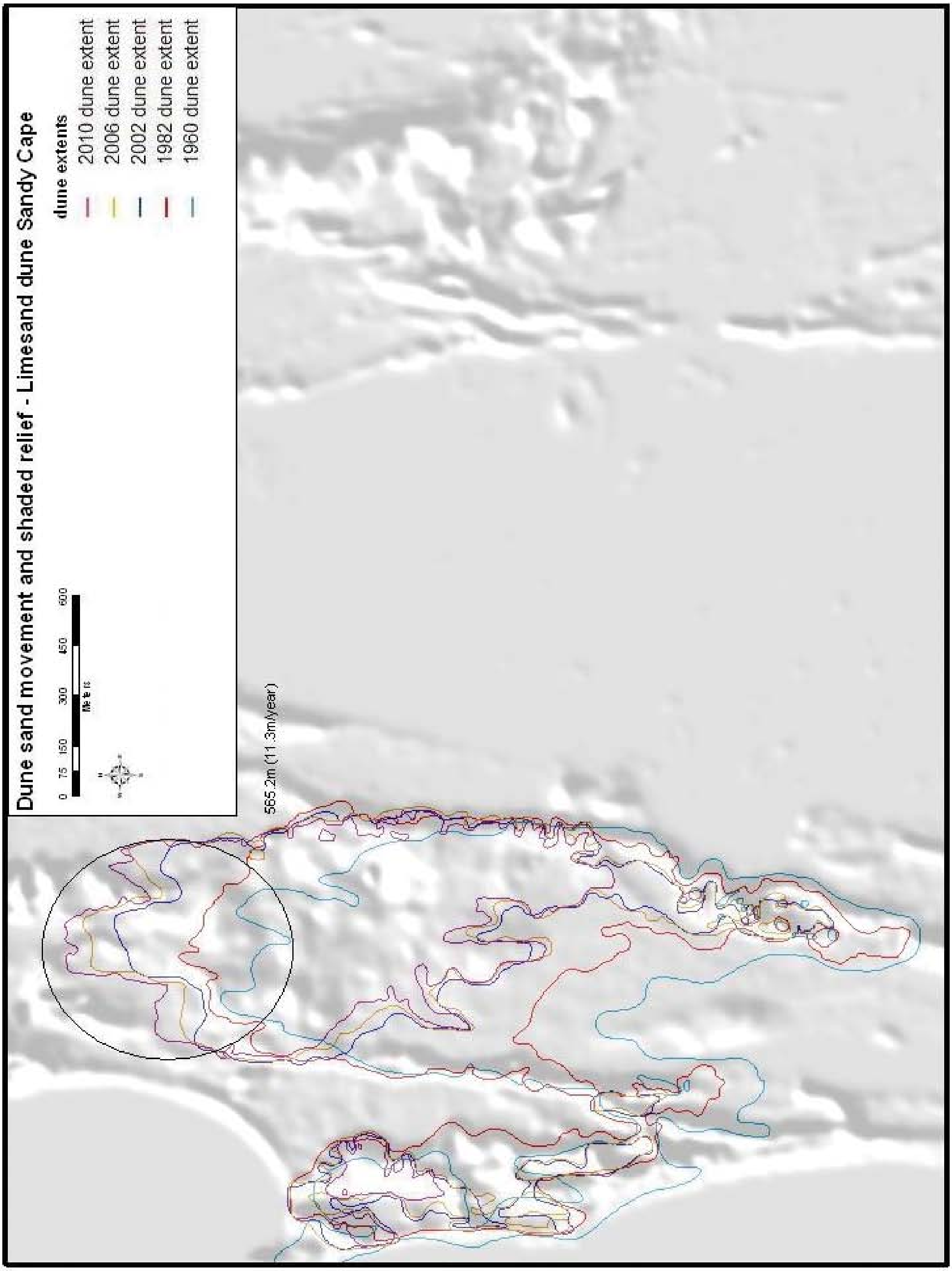
## Limesand dune Green Head South – Migration



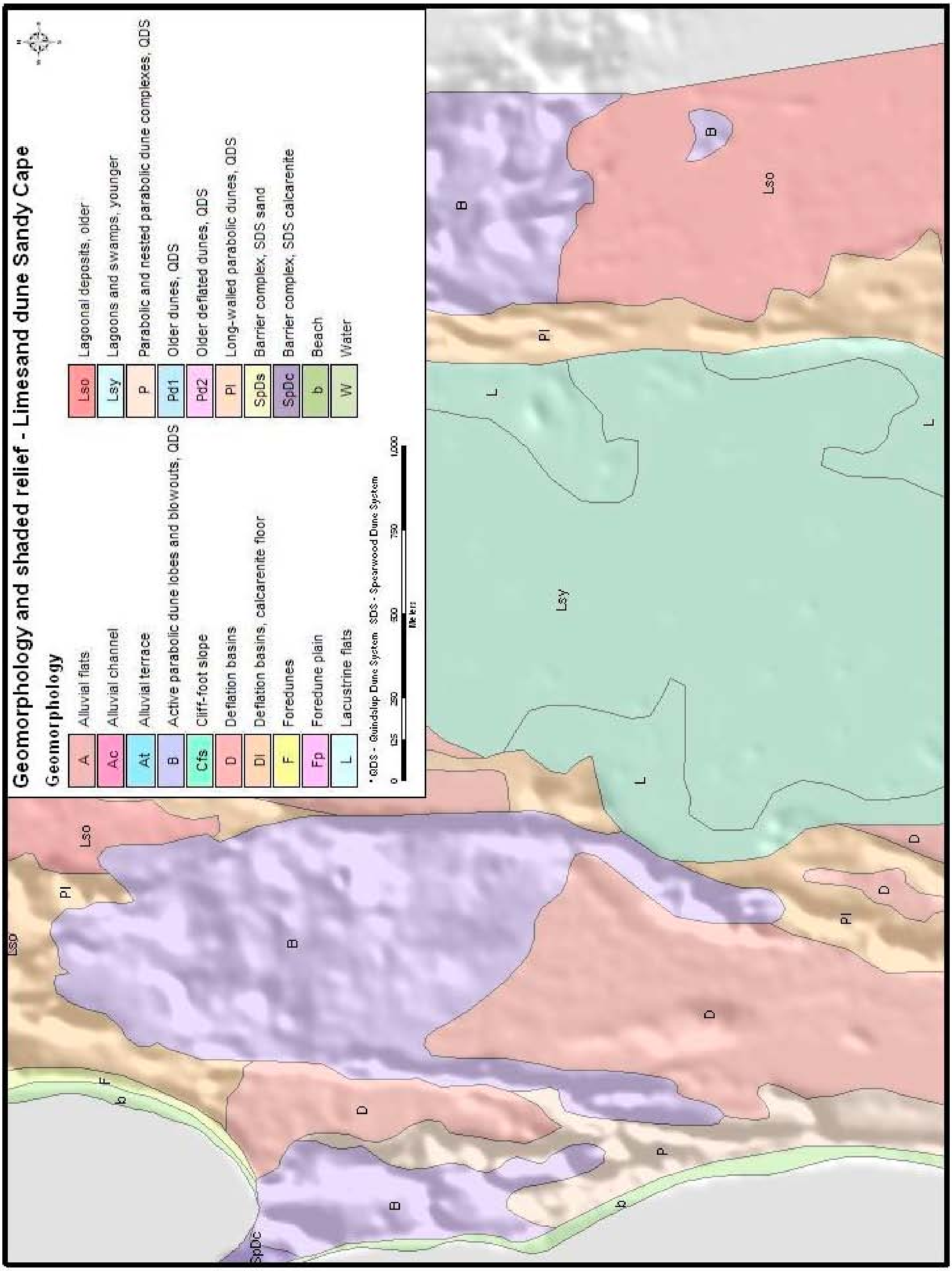
## Limesand dune Green Head South – Geomorphology



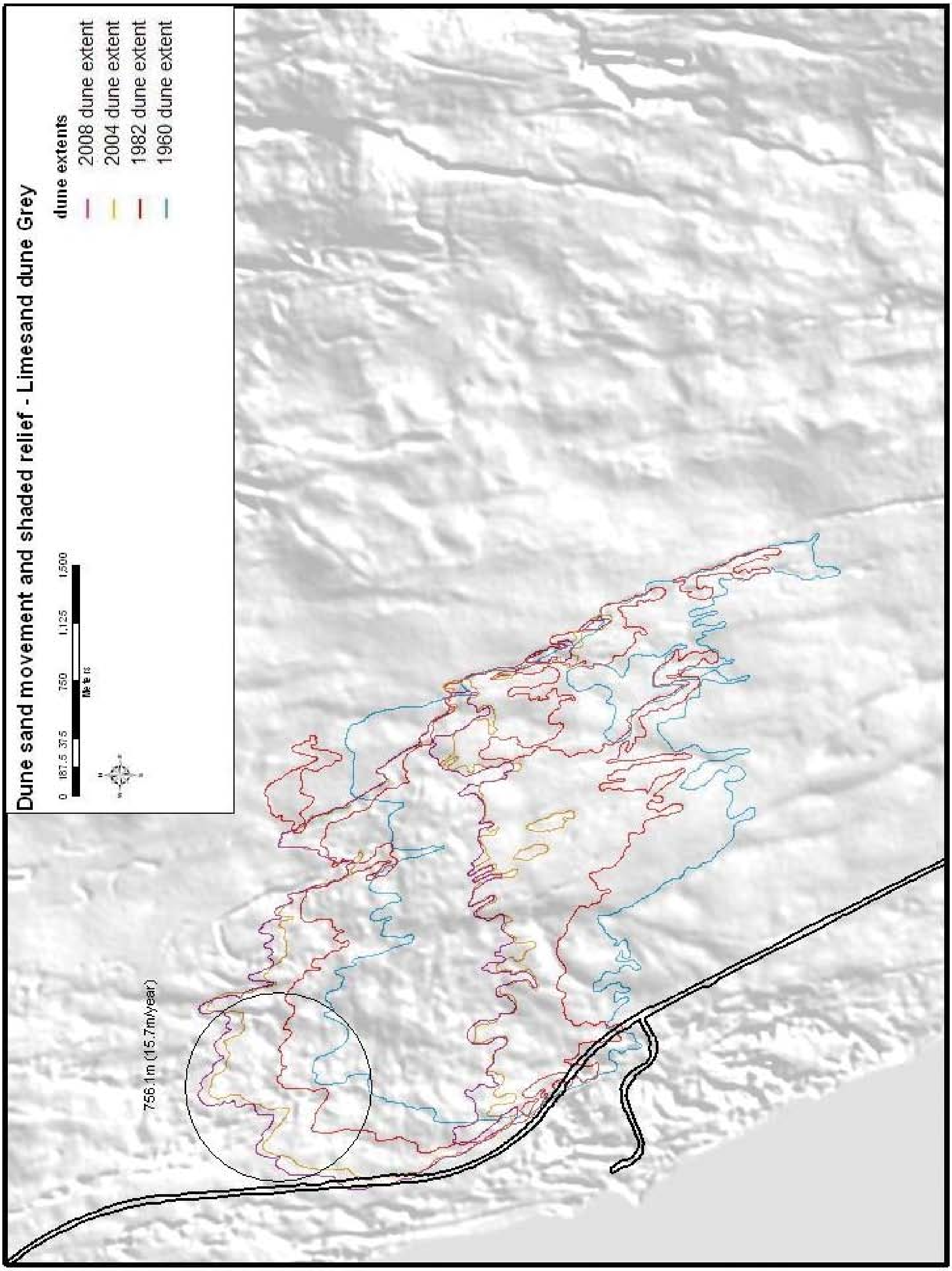
## Limesand dune Sandy Cape – Migration



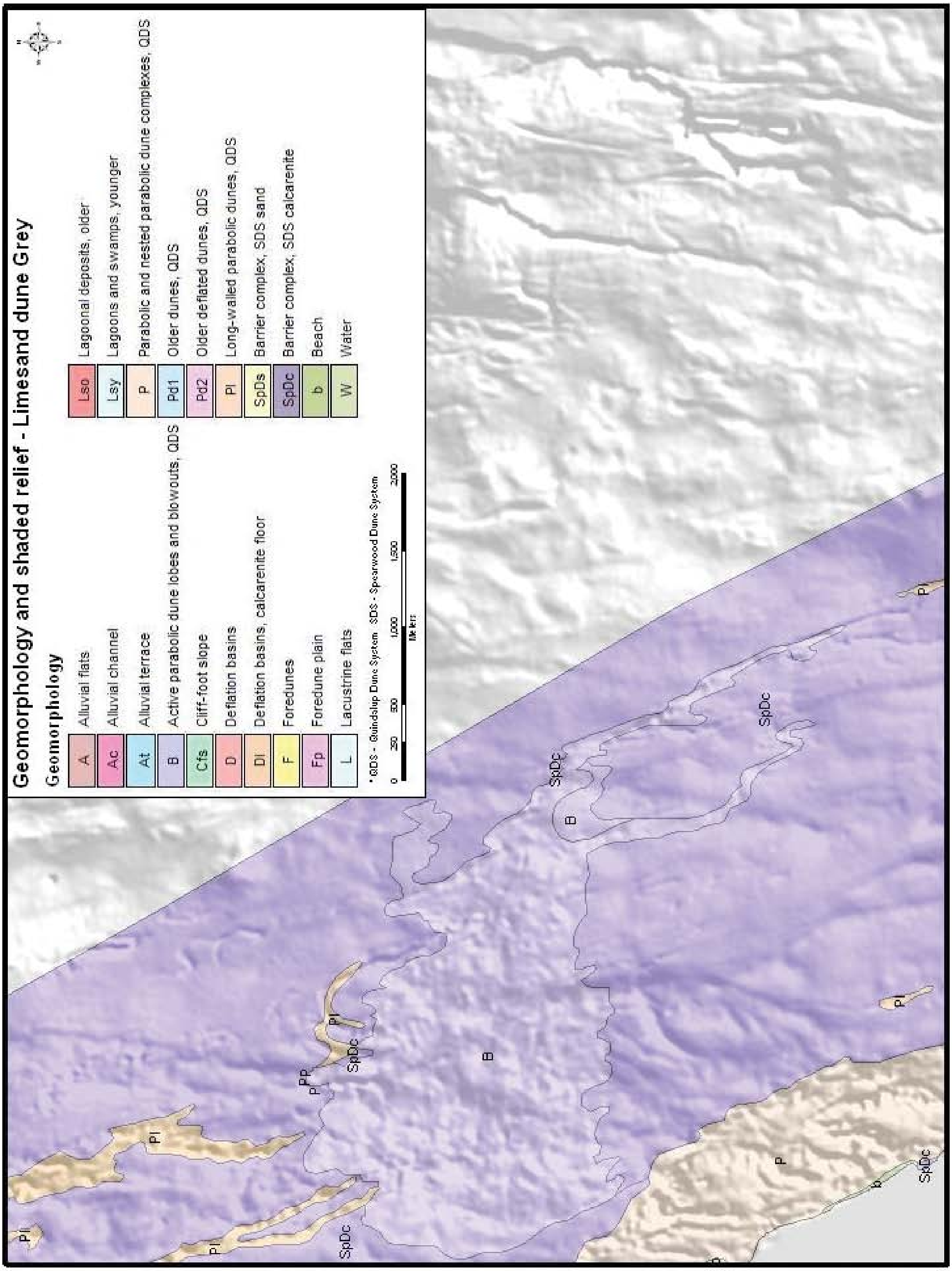
## Limesand dune Sandy Cape – Geomorphology



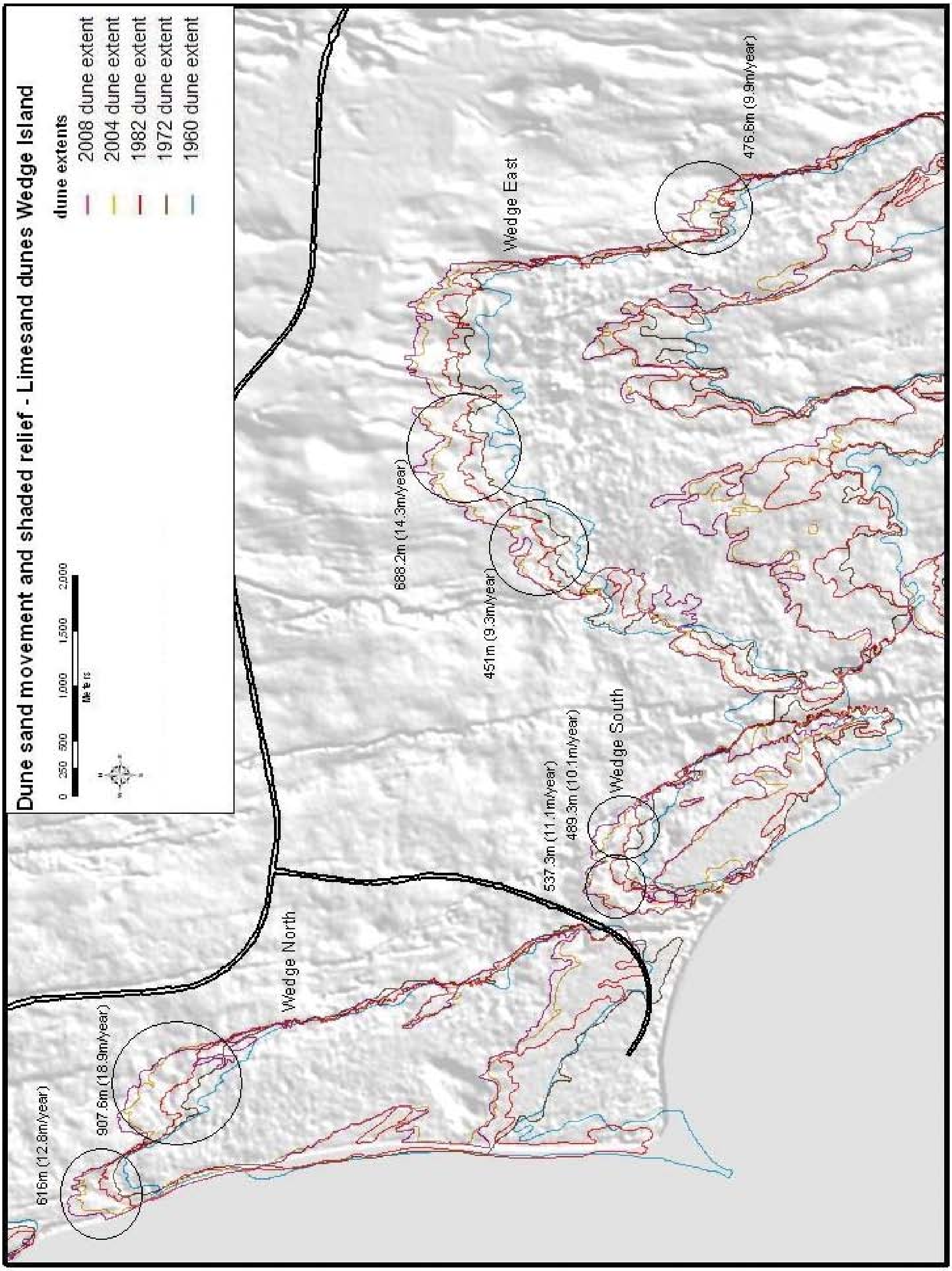
## Limesand dune Grey – Migration



## Limesand dune Grey – Geomorphology



## Limesand dunes Wedge Island – Migration



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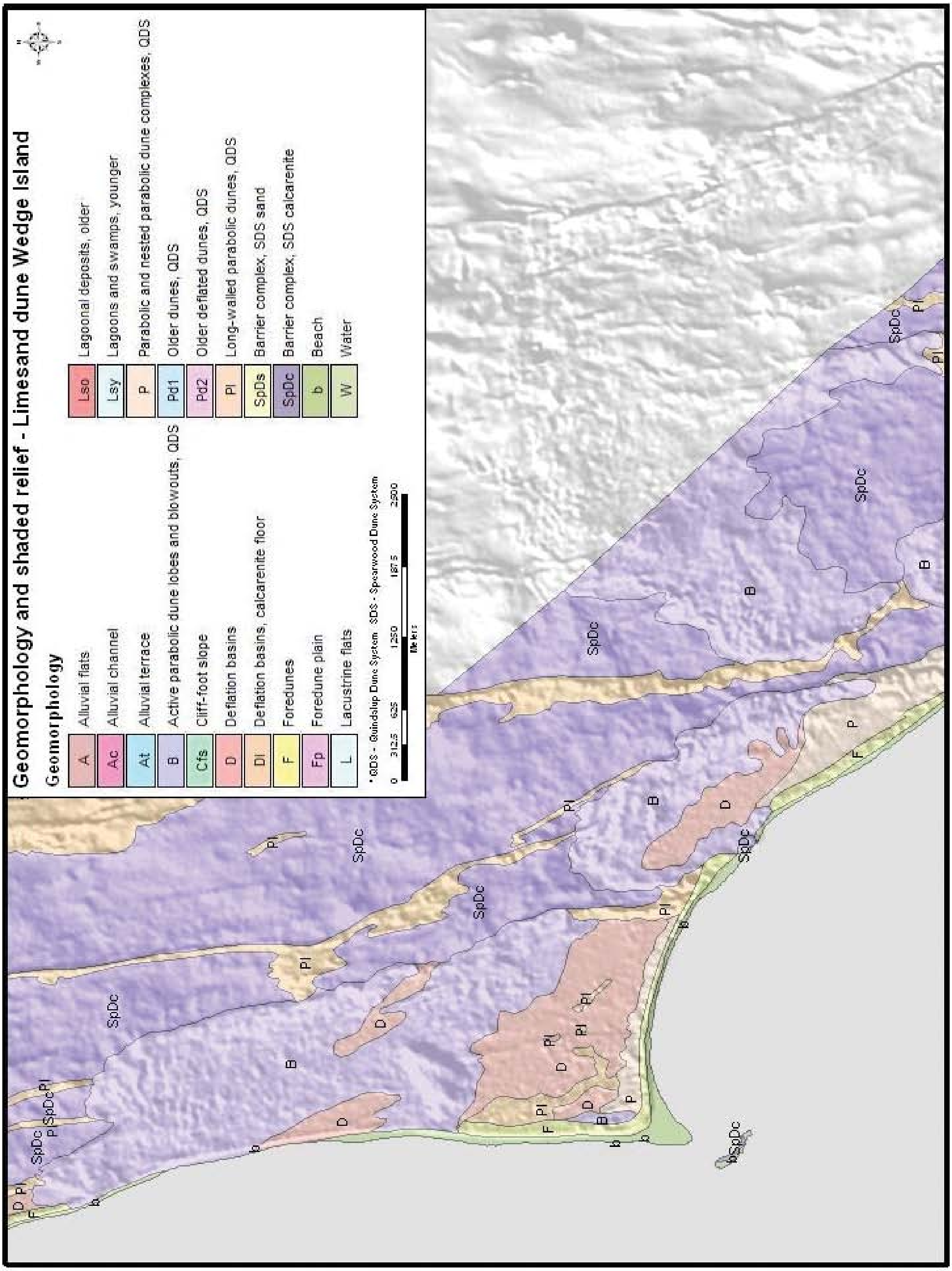

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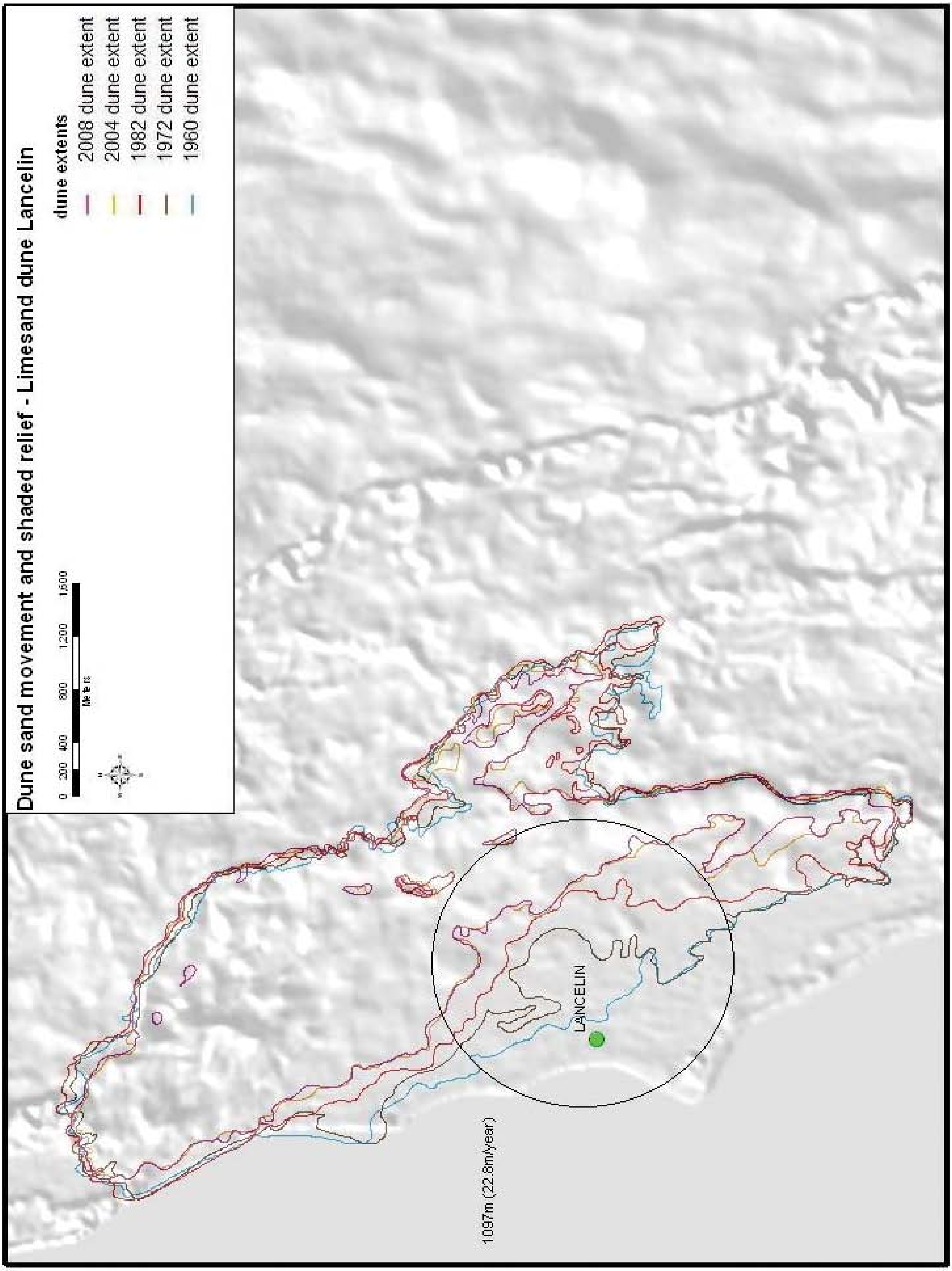
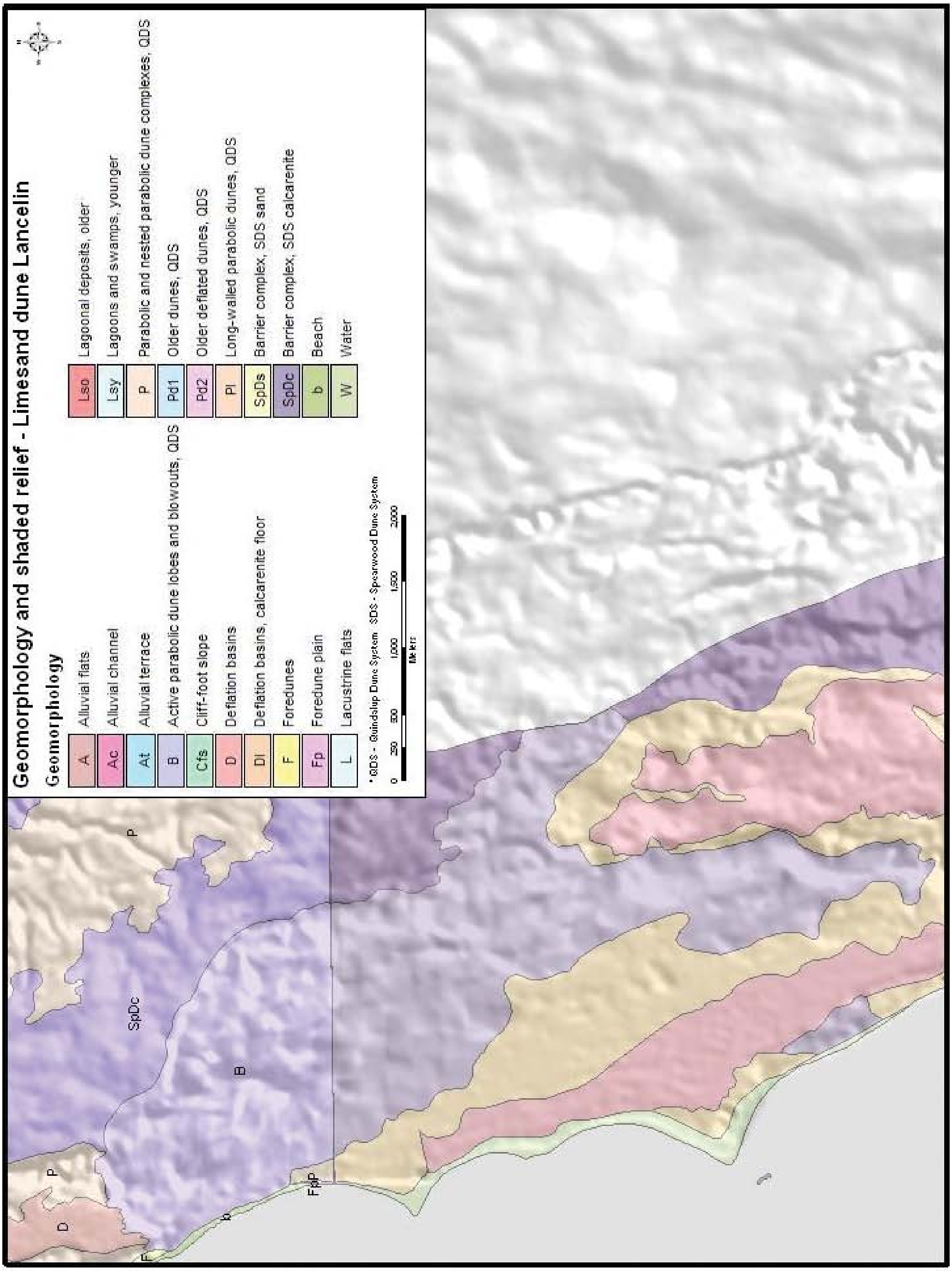


## Limesand dune Lancelin – Geomorphology



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Published February 2017
DMPJAN17_4634