Palaeogeographic reconstructions of western New Guinea from biostratigraphic data

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Abstract

New biostratigraphic analyses of approximately 200 outcrop samples and reinterpretation of the biostratigraphy nearly 100 wells distributed across Indonesian western New Guinea enables reconstruction of the palaeogeography of the region from the Silurian to present day. Biostratigraphic ages and palaeodepositional environments were interpreted predominantly from occurrences of planktonic and larger benthic foraminifera. Palaeogeographic reconstructions reveal two major transgressive-regressive cycles in regional relative sea-level with peaks interpreted to occur in the Late Cretaceous and Late Miocene. During the Late Paleozoic and Early Mesozoic terrestrial deposition was prevalent across much of western New Guinea as it formed part of the northern promontory of the Australian continent, termed the Sula Spur. From the Late Jurassic the first regional transgressive event resulted in increasing water depths until the Late Cretaceous. Carinate planktonic foraminifera are widespread in sediments of this age encountered in wells and outcrop across the entire region. A regressive event from the Late Cretaceous into the Paleogene resulted in widespread shallow water carbonate platform deposition

by the Middle to Late Eocene. A minor transgressive event is recorded during the Oligocene but was cut short by collision between the Australian continent and intra-Pacific island arcs in the Early Miocene causing regional uplift in the region and formation of a subaerial unconformity. Following uplift, carbonate platforms established in shallow water areas depositing youngest units of the New Guinea Limestone Group. A second transgressive event, initiating during the Middle Miocene, reached its peak in the Late Miocene this was followed by a further regression culminating in the present day topographic expression of western New Guinea.

Keywords: New Guinea; planktonic; larger benthic; foraminifera; paleogeography

1. Introduction

New Guinea represents the northernmost boundary of the Australian Plate and has done at least as far back as the Permian when New Guinea was part of an Andean-style arc system that extended around a large portion of Gondwana (Hill and Hall 2003; Hall 2002; 2012; Metcalfe 2009; Gunawan et al., 2012; 2014; Webb and White, 2016). This long-lived plate boundary records evidence of numerous accretion events and pulses of magmatism and metamorphism during the Eocene, Oligocene, Miocene and Pliocene (Baldwin et al., 2012; Baldwin and Ireland; Davies – Review; Pieters et al., 1983; Visser and Hermes, 1962; Pigram; Jaques). However, much of the geology of New Guinea is also dominated by carbonate deposition during seemingly long periods of quiescence (Pieters et al., 1983; Pigram; Visser and Hermes, 1962; Hill; Davies; Baldwin et al., 2012). In this paper we present new biostratigraphic age data based on benthic and planktonic foraminifera as well as facies analyses from nearly 200 outcrop samples and 100 wells from western New Guinea. The aim of this work was to better establish the duration and facies distribution of carbonate deposition to better understand periods of queisence at the northern margin of the Australian Plate between the Silurian and present day.

1.1 The Bird’s Head, Neck, Body and Tail

New Guinea is often described to reflect the shape of a bird, comprising the Bird’s Head, Neck, Body, and Tail from west to east, respectively (Fig. 1). The Bird’s Head, Neck and part of the Body make up the Indonesian provinces of West Papua and Papua (formerly known as Irian Jaya). The rest of the Bird’s Body and Tail make up Papua New Guinea. The island’s peculiar morphology largely reflects the geology and tectonic evolution of the island. For example, the Bird’s Neck is largely composed of limestones and siliciclastic rocks shortened during the development of the Lengguru Fold and Thrust Belt. These deformed rocks form part of a mountain belt that extends from eastern New Guinea (the Bird's Head), along the Central Range (the Bird’s Body) to the eastern tip of the island (Bird’s Tail) (Fig. 1). This paper focuses primarily on the stratigraphic and paleogeographic evolution of the Bird’s Head, Neck and Body.

1.2 Geological Mapping of Western New Guinea

The first comprehensive geological mapping of Indonesian New Guinea was conducted between 1935 and 1960 by geologists of the Nederlandsche Nieuw Guinee Petroleum Maatschappij and is described in great detail by Visser and Hermes (1962). While this work was completed before the advent of the theory of plate tectonics, the observations that are reported in this work are extremely valuable and lay the foundation for the stratigraphy of Irian Jaya. This work was later refined by the Indonesian Department of Mining and Energy’s Geological Research and Development Centre (GRDC) and the Australian Bureau of Mineral Resources (now known as Geoscience Australia) as part of the Irian Jaya Geological Mapping Project between 1978 and 1982; the results of which are summarised in Pieters et al. (1983).

Pieters et al (1983) described the stratigraphy of the Bird’s Head as consisting of three provinces. To the north lies an Oceanic Province of ophiolite and island arc volcanics of Pacific Plate affinity separated from a southern Continental Province of Australian continental affinity separated by a Transition Zone of deformed and metamorphosed rocks (Pieters et al., 1983). The Transition Zone represents a suture marking the collision of the Australian continent with the island arc on the Pacific Plate in the early Miocene (Fig. 1), with continued convergence to this day (Pieters et al., 1983; Milsom, 1992). Thus the stratigraphy of the Bird’s Head can be broadly described as intra-Pacific island arc material to the north and east, and Australian continental material to the south and west, the post-collisional stratigraphy of both domains is reasonably contiguous (Fig. 2). In this paper we focus on carbonates deposited on both the former intra-Pacific island arc and Australian continent.

2. Depositional History of western New Guinea sediments

The oldest strata within the Bird’s Head are found in rocks of Australian continental affinity. The Kemum Formation forms a basement block of metamorphosed fine-grained siliciclastic rocks assigned a Silurian-Devonian age based on the presence of graptolites (Visser and Hemres, 1962; Pieters et al., 1983). Both the Kemum and Aisasjur Formations are reported to comprise distal and proximal turbidite deposits, respectively (Visser and Hermes, 1962; Pieters et al., 1983; Webb and White, 2016). The Modio Dolomite of the Central Ranges is the oldest carbonate unit deposited from the Silurian-Devonian (Fig. 2; Pieters et al., 1983). The Carboniferous to Permian was a period of relatively stable paralic sediment deposition, with occasional shallow marine incursions marked by thin limestone beds in the Central Ranges. The Permo-Carboniferous Aifam Group contains various terrestrial and marine deposits. In this group the Aimau, Ainim and Aiduna formations are reported to contain conglomerates, red beds and coal seams suggesting a terrestrial depositional setting, the Aifat mudstone however may have been deposited in a basinal setting (Pieters et al., 1983).

During the Triassic only arid terrestrial deposits of the Tipuma Formation are known from the Bird's Head, with the nearest known carbonates of this age found in the Late Triassic Manusela and Asinepe Limestone formations of Misool and Seram (Pieters et al., 1983; Martini et al., 2004). Here, early to mid Jurassic calcareous sediments were deposited in shallow seas with little siliciclastic input, however, in the Bird's Head deposition of siliciclastic material forming the Tamrau Formation and Kembelangan Group, persisted throughout the Jurassic and into the Late Cretaceous (Fig. 2).

The Cretaceous siliciclastic units of the Kembelangan Group include the Jass Formation, Piniya Mudstone and the Woniwogi and Ekmai Sandstones. Carbonate deposits in the Bird's Head are not known until the Late Cretaceous (Pieters et al.,

1983) where Coniacian to Maastrichtian age siliciclastics of the Ekmai Sandstone pass laterally into the deep-water pelagic carbonates of the Simora Formation (Fig. 2; Brash et al., 1991). Fragments of inoceramid bivalves within the base of the conformably overlying Waripi Formation suggest a Late Cretaceous age.

From the Late Cretaceous and into the Paleogene there is a distinct change from siliciclastic to carbonate deposition recorded across the Bird's Head. Visser and Hermes (1962) proposed the 'New Guinea Limestone Group' (NGLG) to include Late Cretaceous to Middle Miocene limestones, between 1km and 1.6km thick, that outcrop in the western Bird's Head, through the Lengguru Fold and Thrust Belt, into the Central Range and Papua New Guinea (Brash et al., 1991). The oldest Paleogene strata of the NGLG, the Waripi Formation, were deposited in shallow-water areas of a new Cenozoic basin from the Mid to Late Paleocene (Brash et al., 1991; Fig. 2). Brash et al. (1991) suggest that in deep-water areas to the north of this new basin, the Imskin Limestone may interfinger with the Waripi Formation (Fig. 2). The Cenozoic basin was relatively stable throughout the Eocene, depositing the shallow-water Faumai and Lengguru Limestones, while the Imskin Limestone continued accumulating pelagic carbonate up until collision with the intra-Pacific island arc in the Early Miocene (Fig. 2).

Within the intra-Pacific island arc, carbonate deposition was restricted to patch reefs developed around eroded volcanoes known from the Eocene age Auwewa Formation (Fig. 2), up until the time of collision (Wilson, 2002). Following collision in the early Miocene, carbonate platform development was widespread across much of the Bird's Head. Early to Middle Miocene platform carbonates of the Kais and Maruni

Limestones, and Wainukendi and Wafordori Formations (Fig. 2), were subsequently drowned during a Mid to Late Miocene transgressive event that terminated platform accumulation abruptly (Brash et al., 1991; Gold et al., in review). During the Pliocene, or very latest Miocene, rapid uplift attributed to major thrusting, folding (Wilson, 2002) and strike-slip faulting prevailed in the Bird's Head causing the formation of several basins (Pieters et al., 1983). Erosion of uplifted areas filled these basins with much siliciclastic sediment. Only the islands of Misool and Biak remained starved of siliciclastic sedimentation permitting deposition of platform carbonates of the Wardo, Korem and Mokmer Formations (Fig. 2) in the relatively clear waters (Pieters et al., 1983; Wilson, 2002).

3. Methodology

This paper presents the results of several field campaigns conducted by the Southeast Asia Research Group (SEARG), Royal Holloway, University of London, in the Bird's Head of Indonesian New Guinea. Over these campaigns nearly 200 samples were collected of the New Guinea Limestone and associated carbonate units.

Samples were thin sectioned and examined for carbonate petrography and biostratigraphic dating using planktonic and larger benthic foraminifera, of these 198 samples yielded well-constrained biostratigraphic ages. Ages are assigned using planktonic foraminiferal zones of Blow (1979), Berggren and Miller (1988) and Berggren et al. (1995), recalibrated to Wade et al.'s (2010) sub-tropical planktonic foraminiferal zones. Larger benthic foraminiferal zones are assigned to the Indo-Pacific 'letter stages' of Adams (1965, 1970). We subdivided the biostratigraphic results into 19 time intervals to show the paleogeographic evolution of western New Guinea between the Silurian and Pleistocene.

Palaeogeographic reconstructions were determined using bathymetric preferences of organisms (Hallock and Glenn, 1986; van Gorsel, 1988; Murray, 2006; BouDagher-Fadel, 2008; 2015; Beavington-Penney and Racey, 2004; Lunt, 2013) observed in each sample, summarised in Figure 4. For simplicity in generating the palaeogeographic maps, five relative bathymetries were assigned to samples containing depth-diagnostic foraminiferal assemblages (Fig. 4). Where heterogeneous depositional environments were interpreted at a single locality, the modal depositional setting for that time and location is recorded in the gross depositional maps.

In addition to the new analyses of samples collected across the Bird's Head, biostratigraphic data from 97 wells in the region were reviewed and reinterpreted. Stratigraphic intervals within the wells were assigned to the relative bathymetry scheme using records of foraminiferal occurrences that meet the criteria laid out in Figure 4. Well data used in this study were sourced from a combination of the public domain and SEARG confidential industry data; consequently we are unable to show the location of all wells.

The depositional bathymetries of samples and well intervals interpreted for each time slice were plotted using ArcGIS software so that the spatial distribution of facies could be compared with existing geological maps of the region produced by the GRDC. We used the maps and our new data to draw gross depositional environment maps. These were overlain on the present day configuration of the Bird's Head to show where deepening/shallowing trends can be observed today. The facies maps were plotted according to the present day configuration of western New Guinea, but do not attempt to restore the displacement of faults or large-scale rotation of continental fragments (e.g. Hall 2012; Charlton, 2010). While these maps are somewhat simplified in terms of the region's tectonic history, our aim was to produce a series of maps that could be used to identify the present day distribution of potential hydrocarbon plays.

4. Palaeogeographic reconstructions

4.1 Temporal Trends

Through the reconstruction of palaeodepositional environments using microfossil assemblages, temporal trends of relative sea-level change can also be deduced. Figure 5 displays a localised relative sea-level curve for the Bird's Head region from the Silurian to Pleistocene, based on the palaeogeographic reconstructions of an arbitrary data point within the northern Bintuni bay.

Relative sea-level fall during the Silurian saw the replacement of deep water settings to terrestrially dominated environments persisting from the Permian to Early Jurassic (Fig. 5). Transgression throughout the Middle Jurassic and into the Cretaceous resulted in peak Mesozoic relative sea-level by the Late Cretaceous (Fig. 5) and the deposition of many fine-grained siliciclastic formations. Relative sea-level fell throughout the Paleogene until the Middle to Late Eocene when widespread shallow water areas permitted the growth of extensive carbonate platforms represented by the oldest units of the NGLG including the Faumai, Lengguru and Imskin Limestones, and lenses within the Auwewa Formation.

Relative sea-level increased for a short duration during the Oligocene before the onset and perpetuation of arc-continent collision between the Australian and Pacific Plates in the earliest Miocene (Fig. 2). This collision caused sub-aerial erosion of Paleogene sediments in some areas forming a regional Early Miocene unconformity (Fig. 2). Collisional uplift within other areas, resulting in regional relative sea-level fall (Fig. 5), permitted renewed widespread carbonate platform growth and deposition of Early Miocene units of the NGLG.

Stable shallow-water carbonate deposition of the NGLG continued for at least 6 Myr across much of western New Guinea until a second regional transgressive event initiated in the Middle Miocene (Fig. 5). Relative sea-level rise reached its peak in the Late Miocene, possibly correlating the global Tor1 flooding event (Gold et al., in review), resulting in the deposition of widespread deep-water limestones and fine-grained siliciclastics of the Klasafet and Klasaman Formations. Relative sea-level began to fall again during the Pliocene and continued until the present day (Fig. 5), leaving western New Guinea sub-aerially exposed as we know it today.

4.2 Silurian

During the Silurian, bathymetries in excess of 100m are interpreted across much of the central Bird's Head (Fig. 6). This interpretation is based on published descriptions and distribution of the widespread basement block comprising the

Kemum Formation. Only one well reviewed by this study contained Silurian material, no new analyses of outcrop samples of this age were undertaken in this study.

Water depths greater than 100m are interpreted based on the presence of graptolites, typical of Paleozoic deep-water settings, found within the Kemum Formation. This formation is described to contain sedimentary structures typical of distal turbidites and the Aisasjur Formation, which outcrops at the western extent of the Kemum basement block, is reported to comprise proximal turbidite deposits (Pieters et al., 1983). This suggests the presence of localised north-east directed bathymetric gradient and transport direction for turbiditic material in the central Bird's Head (Fig. 6).

A broad south-easterly shallowing trend towards the Bird's Body is interpreted (Fig. 6). This based on the presence of the Modio Dolomite to the east of the Bird's Neck and encountered within the Cross Catalina-1 well farther to the east in the Bird's Body (Fig. 6). The Modio Dolomite is interpreted by this study to have a shallow-water carbonate-rich protolith, relative to the deeper water sediments to the north-west.

4.3 Carboniferous

Palaeogeographic reconstructions of the Carboniferous are based on published descriptions of formations of this age and review of two wells. No new analyses of outcrop samples were conducted by this study.

Conglomerates, red beds and coal seams observed within the Aimau, Ainim and Aiduna Formations of the Bird's Head and Neck suggest a terrestrial depositional setting during the Carboniferous (Fig. 7; Pieters et al., 1983). This is supported by the presence of plant-bearing terrestrial sediments reported from the Klalin-3 and Puragi-1 wells.

Although the Aifat Mudstone is reported as marine (Pieters et al., 1983), the deposition of this unit may have occurred during the early Carboniferous as the previous period of Silurian high relative sea-level was waning (Fig. 5). Consequently, a widespread terrestrial palaeodepositional setting is interpreted across the region (Fig. 7).

4.4 Permian

The Permian palaeogeography interpreted by this study is based entirely on published lithological descriptions and review of 23 on- and offshore wells. Of these wells, 13 are interpreted to contain shallow water sediments based on occurrences of delta front material and shallow water limestones. Ten wells are interpreted to contain terrestrial deposits comprising combinations of red beds, coals, plants and freshwater palynomorphs.

Permian deposits of western New Guinea are distributed within a narrow terrestrial zone, extending across the central Bird's Head in the north, south into the Bird's Neck and Body (Fig. 8). This terrestrial zone is surrounded by shallow water units, interpreted to have been deposited in water depths no greater than 20m (Fig. 8).

The northern boundary of the terrestrial zone is drawn from the extent of outcrops of the Aimau, Ainim and Aiduna Formations across the Bird's Head and Neck. The southern extent of the terrestrial zone is delineated by well data. No deep-water Aifat mudstone is mapped with the rest of the Aifam Group in Figure 8 as it is interpreted to be older than Permian.

4.5 Triassic

Reconstructions of palaeodepositional environments of Triassic rocks within western New Guinea are based on the distribution of the Tipuma Formation data from 13 wells from the Bird's Head and island of Seram (Fig. 9).

The age of the Tipuma Formation is reported as no older than Late Triassic (Gunawan et al., 2012) based on detrital zircon ages and is described to have been deposited within an arid continental setting comprising unfossiliferous red-bed sequences (Visser and Hermes, 1962; Pieters et al., 1983). This is supported by the presence of oxidised sediments and continentally derived palynomorphs observed within many of the seven wells interpreted to contain terrestrial deposits (Fig. 9). A further six wells contain paralic and/or supralittoral sediments interpreted here to represent shallow water depths, deposited in less than 20m water depth (Fig. 9).

Triassic continental deposits are widespread across much of western New Guinea and Seram (Fig. 9). The Bird's Head is described to have remained in its present position relative to Australia since the Triassic (Gunawan et al., 2012) and these terrestrial deposits may extend farther south as part of the northern promontory of the Australian continent, known as the 'Sula Spur'.

4.6 Early Jurassic

Early Jurassic data points are scarce within this study, with only two wells from the Bird's Head and Body containing material of this age (Fig. 10). These wells contain terrestrial sandstones of the Tipuma Formation, which continued to be deposited until the Early Jurassic (Visser and Hermes, 1962; Pieters et al., 1983; Gunawan et al., 2012). Consequently, a narrow zone of solely terrestrial deposits is interpreted to extend from the Bird's Head, into the Neck and Body (Fig. 10), and possibly farther into Australia as part of the Sula Spur.

4.7 Middle Jurassic

Across western New Guinea, a period of Late Triassic to Early Jurassic terrestrial deposition, lasting at least 28 My, was succeeded deeper water sedimentation during a transgressive event in the Middle Jurassic (Pieters et al., 1990; Lunt and Djaafar, 1991; Gunawan et al., 2012; Figs. 5, 11). This is supported by review of 25 wells containing Middle Jurassic strata and material from eight outcrop locations.

It is interpreted that by the Middle Jurassic, relative sea-level had increased so that much of the Sula Spur was submerged, reducing the once continuous peninsula to an archipelago of isolated landmasses (Fig. 11). Two such landmasses were separated by a narrow seaway with water depths between 50 and 100m (Fig. 11). Terrestrial deposits are interpreted within six wells in the central Bird's Head and southern Bird's Neck based on the presence of continentally derived palynomorphs. A deltaic system is interpreted to the west of the northern landmass due to the presence of fluvio-deltaic sediments reported within the CS-1X well (Fig. 11). These landmasses are flanked by shallow seas of water depths no greater than 20m, described from 18 wells. Water depths in excess of 50m are delineated by outcrops of the Kopai Formation (Fig. 11).

The Kopai Formation is described to comprise deep-water black shales and limestones (Pieters et al., 1983). Close to the village of Wendesi, Kopai Formation black shales contain a common '*Macrocephalites'* ammonite assemblage. This assemblage includes typical North Gondwanan species including *Macrocephalites* *keeuwensis*, *Sphaeroceras boehmi* and *Holcophylloceras indicum* (Fig. 12). This '*Macrocephalites'* ammonite assemblage is assigned a Bathonian-Callovian age (Westermann & Callomon, 1988; Westermann, 1992; Westermann, 2000; van Gorsel, 2012) and were deposited within a distal, deep, open marine setting (van Gorsel, 2012).

The Middle Jurassic Tamrau Formation is described to comprise ammonites, bivalves, and later planktonic foraminifera (Pieters et al., 1983) indicating a relatively deep marine depositional environment. However, the Tamrau block is thought to be allochthonous and translated to its current position along the Sorong Fault Zone since the Pliocene.

4.8 Late Jurassic

Palaeogeographic reconstructions of this time interval are based on review of 26 wells containing Late Jurassic material and the distribution of the Kopai, Tamrau and Woniwogi Formations of the Bird's Head, and Demu and Lelinta Formations of Misool island. No outcrop samples were collected or examined of Late Jurassic age.

Continued regional transgression into the Late Jurassic (Fig. 5) saw the seaway between the two landmasses of the former Sula Spur attain water depths in excess of 100m (Fig. 13). The deltaic system to the west of the northern landmass is interpreted to persist into the Late Jurassic due to the presence of sediments reported within the CS-1X well (Fig. 13).

The Woniwogi, Demu and Lelinta Formations are interpreted to be deep-water marine deposits, similar to the Kopai and Tamrau, based on the presence of glauconitic and argillaceous, fine-grained, distal sediments (Pieters et al., 1983) and bathyal agglutinated foraminifera such as *Glomospira* spp, and *Trochammina* spp. within some wells (Murray, 2006).

4.9 Early Cretaceous

Only 10 of the reviewed wells contained material interpreted to be Early Cretaceous in age, no outcrop samples were collected from this time interval. In addition to the deep-water Kopai, Tamrau, Woniwogi, Demu and Lelinta Formations, the widespread Early Cretaceous Piniya Mudstone is also interpreted to be a deep marine deposit that comprises thinly bedded glauconitic black mudstones and muddy siltstones (Pieters et al., 1983).

Due to the distribution of the Piniya Mudstone across the central Bird's Head, it is interpreted that the northern remnant landmass of the Sula Spur was submerged at this time beneath water depths in excess of 100m (Fig. 14). This is supported by the presence ammonites and belemnites within the Kembelangan-1 well (Visser and Hermes, 1962) and carinate Globotruncanid planktonic foraminifera, such as *Praeglobotruncana* spp., *Paraglobotruncana* spp. and *Rotalipora* spp., in the Kembelangan-1 and Noordwest-1 wells.

A bathymetric gradient shallows towards the south-west where water depths between 50m and 100m are interpreted (Fig. 14). This is based on the presence of shelfal agglutinated and calcareous benthic foraminifera, such as *Lenticulina* spp., in the Onin East-1 well and sediments dominated by globular planktonic foraminifera including *Hedbergella* spp., *Heterohelix* spp. and *Ticinella* spp., and lack of carinate foraminifera, within the Kola-1 well. A small area to the south of the Bird's Body remained subaerially exposed based on shallow water sandstones encountered in the Cross Catalina-1 well.

Although the Woniwogi Formation is assigned a Late Jurassic to Early Cretaceous age (Pieters et al., 1983), the planktonic foraminifera listed above (recorded from the Woniwogi Formation in the Kembelangan-1, Noordwest-1 and Kola-1 wells) indicate a restricted late Early Cretaceous, Aptian-Albian, age.

4.10 Late Cretaceous

Relative sea-level rise reached its peak during the Late Cretaceous (Fig. 5) where water depths in excess of 100m are interpreted across the whole of western New Guinea (Fig. 15). This is evident from data reviewed from 40 wells and six outcrop samples, together with the distribution of Late Cretaceous deep-water sediments of the Tamrau and Jass Formations, Piniya Mudstone, Amiri Sandstone of New Guinea and pelitic rocks of the Korido Metamorphics of the island of Supiori (Fig. 15). Late Cretaceous shallow-water Ekmai sandstones are interpreted to have been deposited farther afield and brought into the Bird's Neck area through shortening in the Lengguru Fold and Thrust Belt. The '*in situ'* facies in the Bird's Neck is interpreted to be represented by the deep marine Piniya Mudstone, following the trend for increasing sea-level initiating in early Jurassic.

Many of the 40 wells contain diagnostic deep-water taxa, dominated by carinate Globotruncanid planktonic foraminifera including, but not exclusively, Abathomphalus *mayaroensis*, *Dicarinella* spp., *Gansserina gansseri*, *Globotruncana aegyptiaca*, *Globotruncana arca*, *Globotruncana linneiana*, *Globotruncana ventricosa*, *Globotruncanita* spp., *Globotruncanita stuartiformis*, *Helvetoglobotruncana helvetica*, *Marginotruncana* spp., *Rosita* spp., *Rosita fornicata*, *Rotalipora* spp., *Rugoglobotruncana* spp., *Whiteinella* spp., *Whiteinella archeocretacea*, and globular planktonic foraminifera including *Heterohelix* spp., *Pseudoguembelina* spp. and *Racemiguembelina fructicosa*. Where these carinate planktonic foraminifera occur in abundance, this may indicate water depths in excess of 300m and an upper bathyal depositional setting.

Campanian to Maastrichtian age sediments were collected from the Imskin Limestone to the south-east of the Bird's Head (Fig. 15). Six samples contain deep-water taxa, indicative of outer neritic to lower bathyal water depths in excess of 100m, including *Abathomphalus mayaroensis*, *Contusotruncana fornicata*, *C. plummerae*, *Gansserina gansseri*, *Globotruncana arca*, *Globotruncana linneiana*, *Globotruncanita conica*, *Gta. stuarti*, *Rugotruncana subcircumnodifer* and *Heterohelix* spp (Fig. 16).

4.11 Paleocene

Following the Late Cretaceous relative sea-level high, water levels receded during the Paleocene (Fig. 5) leaving shallower water areas around the southern Bird's Head, Neck and Body (Fig. 17). This is based on review of 34 wells and examination of five outcrop samples collected from the Imskin Limestone. The distribution of shallow water areas up to 20m water depth is delineated by the distribution of the Waripi Formation in outcrop, and encountered in wells particularly in the southern Bird's Body (Fig. 17). The Waripi Formation is interpreted to comprise a shallow-water limestone containing abundant oolites, miliolids and bryozoa (Visser and Hermes, 1962; Brash et al., 1991). Farther north, particularly within the Bintuni basin, deeper waters in excess of 100m are encountered in many wells recording turbiditic material and carbonate mudstones comprising carinate and globular foraminifera including *Morozovella* spp., *M. acuta*, *M. aequa*, *M. angulata*, *M. edgari*, *M. inconstans*, *M. pseudobulloides*, *M. velascoensis*, *Acarinina* spp., *Eugubina* spp., *Globanomalina* spp. and *Subbotina* spp.

Five samples collected from the Imskin Limestone near the island of Rumberpon were dated to be Paleocene age. All samples are interpreted to have been deposited in an outer neritic to lower bathyal setting where water depths exceed 100m (Fig. 17). These samples contain a planktonic foraminiferal assemblage comprising globular and carinate morphologies including *Acarinina coalingensis*, *A*. *primitiva*, *Globanomalina imitata*, *G*. *ovalis*, *Morozovella aequa*, *M*. *angulata*, *M*. *conicotruncata*, *Subbotina* spp. and *Turbeogloborotalia compressa*.

4.12 Early Eocene

Relative sea-level fall continued into the Early Eocene (Fig. 5) and more shallow water areas developed within the central Bird's Head (Fig. 18). This is supported from review of 25 wells, examination of nine outcrop samples and distribution of the Faumai Limestone (Fig. 18).

The Faumai Limestone is described to contain shallow water carbonate bank and shoal deposits and reefal facies (Pieters et al., 1983). This is supported by well data where shallow water areas up to 20m in depth are interpreted north of the Bintuni basin in southern Bird's Neck and Body based on the presence of alveolinids including *Lacazinella* spp. and *Fasciolites* spp. Moderate water depths between 20m and 50m are interpreted from the Faumai Limestone of several wells and outcrop samples that contain alveolinids as well as abundant large, flat, rotaliine foraminifera such as *Assilina* spp., *Cycloclypeus* spp., *Discocyclina* spp. and *Operculina* spp. Pieters et al. (1983) date the Faumai Limestone as Middle Eocene to Oligocene in age, however based on the presence of these alveolinids including *Alveolina* *globosa*, *A*. *laxa* and *A*. *subpyrenaica*, and larger benthics including *Asterocyclina* spp., *Discocyclina ranikotensis* and *Cuvillierina* spp. (Fig. 19), we interpret the Faumai Limestone to be at least as old as Early Eocene, Ypresian, correlating to planktonic foraminiferal zone E1 and Indo-Pacific letter stage 'Ta2' (Fig. 2).

Deeper water areas are interpreted to persist in the wells of the Bintuni basin, from outcrop samples collected close to the island of Rumberpon and the Wandaman Peninsula on the west coast of Cenderawasih Bay and in offshore areas west of New Guinea (Fig. 18). The Bintuni wells contain mixtures of Early Eocene globular and carinate planktonic foraminifera including *Morozovella* spp., *M*. *aragonensis*, *M*. *formosa*, *M*. *quetra*, *M*. *subbotinae*, *Acarinina* spp., *Acarinina nitida* and *Subbotina* spp. Rocks collected from the Imskin Limestone and Wandaman Peninsula also suggest water depths greater than 100m (Fig. 18). Samples collected from these localities contain the planktonic foraminifera *Acarinina* spp., *Acarinina bulbrooki*, *A*. *decepta*, *Globigerina lozanoi*, *Globigerinatheka* spp., *Morozovella formosa*, *M*. *lensiformis*, *M*. *subbotinae* and *Subbotina* spp (Fig. 19).

4.13 Middle - Late Eocene

The lowest Paleogene relative sea-level occurred across much of western New Guinea during the Middle to Late Eocene (Fig. 5). Shallow water areas were prevalent across the central Bird's Head and Seram, and extended throughout the southern Bird's Neck and Body (Fig. 20). This is supported from review of 39 wells, examination of 13 outcrop samples and distribution of the oldest units of the NGLG observed to contain Middle to Late Eocene aged microfaunal assemblages (Fig. 20).

Well data from the offshore Salawati and Bintuni basin areas, Arafura Sea, and onshore wells indicate the presence of shallow waters no greater than 20m depth punctuated by isolated reefal build-ups across most of the central Bird's Head (Fig. 20). This is based primarily on the presence of shallow water and reef loving taxa such as *Alveolina* spp., *Fasciolites* spp., *Lacazinella wichmanni*, *Nummulites* spp., *Nummulites djodjarkartae*, *Pararotalia* spp. and corals observed in wells ASA-1X (Darman, 2000), Aum-1, Boka-1X, Merak Emas-1, Rawarra-1 (Decker, 2009), Sago-1, Sebyar-1 and TBE-1X. Bathymetric gradients away from the shallow water platforms drop to depths approaching 50m (Fig. 20) where large flat rotaliines including *Assilina* spp., *Discocyclina* spp., *Heterostegina* spp., *Operculina* spp. and assemblages of small calcareous benthic foraminifera typical of shelf settings are found in wells Kamakawala-1, Makiri-1D, Tarof-2 and Wos-1. Deep water facies are interpreted in the Onin East-1 well based on the presence of *Acarinina* spp., *Globigerinatheka* spp. and *Morozovella* spp.

Interpretations from well data are supported by outcrop evidence from the western Cenderawasih Bay. Close to the village of Ransiki, shallow water facies include grainstones containing large *Alveolina elliptica* and *Nummulites gizehensis* within samples of the Faumai Limestone (Fig. 21). Farther to the south-east of Ransiki, samples contain large flat rotaliines including *Assilina exponens*, *Asterocyclina* sp. and *Discocyclina sella* indicative of moderate water depths. Water depths between 50m and 100m are interpreted close to the island of Rumberpon (Fig. 20), where rocks of the Imskin Limestone contain the planktonic foraminifera *Acarinina intermedia*, *Globigerina tripartita*, *Porticulasphaera mexicana* and *Subbotina* spp. Rocks of the Imskin Limestone and Wandaman Peninsula indicate outer neritic water depths in excess of 100m surrounding the Wandaman peninsula. Samples here contain a mixture of globular planktonic foraminifera including *Acarinina decepta*, *A*. *pentacamerata*, *A*. *primitiva*, *A*. *pseudotopilensis*, *Globigerinatheka* sp., *Subbotina eocaenica* and carinate forms including *Morozovella aragonensis* and *M*. *crassata*.

The oldest foraminifera observed on the islands of Biak and Supiori are *Pellatispira* sp., an exclusively Late Eocene, Priabonian, aged genus indicative of Indo-Pacific 'letter stage' Tb (Adams, 1970; Figs. 2 & 21). These larger benthic foraminifera are found reworked within clasts of Auwewa Formation material within the Batu Ujang Conglomerate outcropping around Wafordori Bay on the north coast of Supiori. Although reworked, *Pellatispira* sp. signify moderate water depths up to several 10's of metres within the vicinity of Supiori. This taxon is also observed within the Auwewa Formation encountered in wells H-1, Muwar-1, O-1 and R-1 in eastern Cenderawasih Bay and Mamberamo region.

4.14 Oligocene

Relative sea-level rose for a short while across western New Guinea during the Oligocene (Fig. 5). Palaeogeographic reconstructions of this time interval are based on review of 25 wells, examination of six outcrop samples and distribution of the Sirga Formation (Fig. 22).

Small islands of terrestrially derived Oligocene sediments are interpreted in the Bird's Neck from wells Suga-1 and ASB-1X (Fig. 22). These are surrounded by shallow bodies of water with occasional reefal build-ups interpreted based on the presence of *Austrotrillina* spp. and *Nummulites* spp recorded from several wells, including TBE-1X (Fig. 22). Water depths up to 50m are extensive around the southern Bird's Head and Neck (Fig. 22) are denoted by the presence of larger benthic foraminifera including *Cycloclypeus* spp., *Heterostegina borneensis*, *Operculina* spp. and *Pararotalia metacapensis*. Deeper waters are interpreted in the Salawati basin region, Seram Sea and much of the central Bird's Head (Fig. 22) where Oligocene aged rocks, including those of the Sirga Formation, are dominated by intermediate water depth taxa such as *Catapsydrax* spp., *Globigerina ampliapertura*, *Globoturborotalita ouachitaensis*, *Paragloborotalia opima* recorded from Klalin-1, Merak Emas-1 and Siganoi-1.

Six samples of Early and Late Oligocene age were collected from the west coast of Cenderawasih Bay (Fig. 22). Shallow water reef front facies, representing water depths no greater than 10m, are found near the island of Rumberpon where samples contain specimens of *Neorotalia* sp. and one of the last species of *Nummulites*, the reticulate *N. fichteli* (BouDagher-Fadel, 2008).

Late Oligocene rocks are observed in sedimentary lenses of the Arfak Volcanics of the eastern Bird's Head and Auwewa Formation on Supiori (Fig. 22). These samples consist of planktonic foraminiferal packstones and wackestones indicating outer slope depths between 50m and 100m. Planktonic foraminifera of 'intermediate-water' depths consist of globular morphologies including *Globigerina gortanii*, *Globigerina praebulloides*, *Globigerinoides primordius* and *Globoquadrina binaiensis*.

4.15 Early Miocene

The Early Miocene saw the presence of widespread shallow water carbonate platforms across western New Guinea and Cenderawasih Bay, with maximum water depths no greater than 50m (Fig. 23). This is supported from review of 50 wells and examination of 37 outcrop samples. Early Miocene aged units of the NGLG including the Kais, Koor and Maruni Limestones of New Guinea, the Wurui Limestone of Yapen, and Wainukendi and Wafordori Formations of Biak and Supiori are described to comprise predominantly shallow water to reefal carbonates (Visser and Hermes, 1962; Pieters et al., 1983). These units were mapped without distinction between shallow and relatively deeper water facies; therefore the distribution of these formations is used only to interpret water depths no greater than 50m to accommodate potential heterogeneity within the NGLG.

A broad platform populated by reefal build-ups extending from the western Bird's Head to the southern Bird's Neck and Body (Fig. 23). This is interpreted from 41 wells comprising packstones, grainstones and reefal rudstones and floatstones that contain shallow water taxa including *Alveolinella praequoyi*, *Amphistegina* spp., *Austrotrillina* spp., *Borelis* spp., *Flosculinella* spp., *Lepidocyclina* spp., miliolids, *Miogypsina* spp., *Miogypsinoides* spp., *Spiroclypeus* spp. and other organisms including sponges, coral, echinoids and bivalves. Further shallow water platforms are interpreted to have occurred across Cenderawasih Bay, encompassing the islands of Yapen, Biak and Supiori (Fig. 23). These platforms sit atop an extensive body of water no greater than 50m (Fig. 23) based on the presence of the larger benthic foraminifera *Operculina* spp., *Heterostegina* spp. and *Cycloclypeus* spp. Rare deeper water sediments were encountered in the Oseil-1 of Seram contained the globular planktonic foraminifera *Globigerinoides* spp, *Globigerina* spp. and *Catapsydrax* spp.

In outcrop, many reefal carbonates are observed at the base of the Kais and Maruni Limestones of the mainland and Wainukendi Formation of Biak and Supiori. These reefs are mapped isolated patch reefs in Figure 23, although their lateral extent is unknown. Reefal carbonates and those deposited in moderate water depths were observed to contain an abundant and diverse fossil assemblage, predominantly comprising larger benthic foraminifera including: *Eulepidina badjirraensis*, *Lepidocyclina brouweri*, *L*. *isolepidinoides*, *L*. *nephrolepidinoides*, *L*. *oneatensis*, *L*. *stratifera*, *L*. *sumatrensis*, *Heterostegina borneensis*, *Miogypsina intermedia*, *M*. *kotoi*, *M*. *tani*, *Miogypsinoides bantamensis*, *Mdes*. *dehaarti*, *Miogypsinodella primitiva*, *Miolepidocyclina*, *Operculina* sp. and *Spiroclypeus tidoenganensis* (Fig. 24).

4.16 Middle Miocene

A second regional transgressive event is interpreted to have initiated in the Burdigalian (Gold et al., in review) so that by the Middle Miocene much of western New Guinea was submerged in water up to 100m depth (Fig. 25). Evidence for a rise in relative sea-level can be found in deep water facies of the Napisendi Formation and Sumboi Marl of the islands of Cenderawasih Bay, and in drowning successions at the top Maruni and Kais Limestone (Gold et al., in review).

Early Miocene shallow water carbonate platforms were replaced by more moderate water depths in the Salawati and Bintuni basins, and areas south of the Bird's Head while backstepping to shallow water regions to the north-east of the island of Supiori

(Fig. 25). Taxa indicative of moderate water depths, including *Cycloclypeus* spp., *Operculina* spp., and *Pseudorotalia* spp., are prevalent in 18 wells distributed across western New Guinea (Fig. 25). Isolated carbonate platforms and occasional pinnacle reefs are recorded in the main basins of the Bird's Head which contain the shallow water taxa *Alveolinella quoyi*, *Flosculinella bontangensis*, *Lepidocyclina* spp., *Marginopora vertebralis*, *Miogypsina* spp. as well as corals, red algae, bivalves and echinoids. Deeper water areas are interpreted from the presence of planktonic foraminiferal assemblages including the taxa: *Orbulina universa*, *Globigerina druryi*, *Globigerinoides subquadratus*, *Globigerinoides diminutus*, *Globigerinoides bisphaericus*, *Praeorbulina glomerosa*, *Praeorbulina transitoria*, *Paragloborotalia siakensis*, *Globorotalia fohsi*.

Shallow water deposits collected from outcrop include soritid foraminifera such as *Marginopora vertebralis*, and miliolids including *Quinqueloculina* spp. and *Alveolinella quoyi* observed in the Koor Formation situated in the Tosem Mountains in the northern 'cap' of the Bird's Head and interbedded within the Napisendi Formation on Biak. An isolated reef is interpreted near the island of Rumberpon at this time (Fig. 25), where samples contain reef-loving organisms such as miogypsinid and lepidocyclinid larger benthic foraminifera.

Samples from the Kais and Maruni Limestones of the Bird's Head and the Wafordori Formation on Biak contain large flat rotaliine foraminifera including *Katacycloclypeus annulatus* and *Cycloclypeus carpenteri*, lepidocyclinids including *Lepidocyclina brouweri*, *L. ferreroi*, *L. omphalus*, *L. verbeeki*, miogypsinids including

Miogypsinoides indica, *Miogypsina cushmani*, *M*. *intermedia*, *M*. *kotoi*, *M*. *regularia* (Fig. 26).

Deep water deposits occur in the upper parts of the Kais and Maruni Limestones and Napisendi Formation, extending south to the central Bird's Head and Cenderawasih Bay (Fig. 25). These samples contain abundant globular planktonic foraminifera that indicate intermediate water depths between 50m and 100m. Examples include *Orbulina suturalis*, *O*. *universa*, and many species of *Globigerinoides* including *G*. *quadrilobatus*, and *G*. *trilobus* , amongst others and rare Globorotalia spp. (Fig. 26).

<u>4.17 Late Miocene</u>

Relative sea-level continued to rise so that water depths greater than 50m were widespread across much of the present day western New Guinea during the Late Miocene (Figs. 5 & 27). Deep water facies rocks are represented by the Befoor and Klasafet Formations of the Bird's Head and Neck, encountered in 67 of the reviewed wells and in 24 outcrop samples (Fig. 27).

Evidence for the prevalence of water depths between 50m and 100m in the eastern Bird's Head and islands to the north of Cenderawasih Bay come from the abundance of 'intermediate-water' species including *Candeina nitida* and *Orbulina suturalis* (Bé, 1977) found in outcrop samples. Farther south, in samples collected close to the island of Rumberpon (Fig. 27), water depths in excess of 100m are interpreted due to abundance of carinate planktonic foraminifera including *Globorotalia plesiotumida*, *Truncorotalia ronda* and the thick-walled globular planktonics *Sphaeroidinellopsis subdehiscens* and *Globoquadrina dehiscens*. These water depths are interpreted from wells in the Salawati and Bintuni basins, and Arafura Sea, based on the presence of thick-walled and carinate planktonic foraminifera including those mentioned above and *Dentoglobigerina baroemoensis*, *Globorotalia merotumida*, *Neogloboquadrina acostaensis*, *Neogloboquadrina humerosa* and *Sphaeroidinellopsis* spp.

4.18 Early Pliocene

Open marine settings remained the dominant depositional environment across western New Guinea during the Early Pliocene (Fig. 28). Deep water facies are recorded from the Klasaman, Opmorai and Befoor Formations of the Bird's Head, and Wardo, Korem and Kurudu Formations of the islands of Cenderawasih Bay (Fig. 28). Water depths in excess of 50m are recorded from 59 wells across western New Guinea (Fig. 28) that contain microfossils assemblages dominated by globular and carinate planktonic foraminifera including *Globigerina* spp., *Globigerinoides* spp., *Globorotalia* spp., *Neogloboquadrina* spp., *Sphaeroidinella* spp. and *Sphaeroidinellopsis* spp.

Relatively shallower water facies are recorded from 9 wells south and west of the Bird's Head and in the central Bird's Body (Fig. 28). This is supported by the presence of shallow water facies including grainstones, coral floatstones and back-reef lagoonal wackestones that contain the taxa *Ammonia* spp., *Amphistegina lessonii*, *Calcarina spengleri*, *Heterostegina* spp., *Marginopora* spp., *Neorotalia calcar*, *Pararotalia* spp., *Peneroplis* spp., *Pseudorotalia* spp. and miliolids.

Outcrop samples collected from the Befoor and Klasaman Formations in the eastern Bird's Head were observed to contain abundant globular planktonic foraminifera including many species of *Globigerinoides* spp., *Neogloboquadrina* spp., *Pulleniatina* spp., *Sphaeroidinella* spp. and *Sphaeroidinellopsis* spp., as well as *Orbulina universa*. Carinate planktonic foraminifera such as species of *Globorotalia* spp. are interpreted to have been occasionally washed in to this environment and large flat benthic foraminifera such as *Operculina* spp. are washed down slope. To the north-east of the Bird's Head, evidence for shallower reefal settings are observed with reef front facies rocks of the Wai Limestone containing *Calcarina spengleri*, *Amphistegina* spp. and abundant rodophyte red algae situated in front of back-reef facies units (Fig. 28). Shallow water facies, interpreted as back-reef lagoons, to the east of the Bird's Head (Fig. 28) contain soritid foraminifera including *Marginopora vertebralis*, small rotaliids including *Quasirotalia guamensis* as well as delicate corals and the dasycladacean green alga, *Halimeda*.

On the islands of Biak and Supiori, a small bathymetric high is interpreted to pass quickly from inner slope sediments into outer neritic settings indicating the presence of steeply inclined slopes around the high (Fig. 28). Outer neritic sediments representing water depths in excess of 100m occur towards the Biak basin to the south-west. These sediments contain common carinate planktonic foraminifera including *Globorotalia conoidea*, *G. margaritae*, *G. menardii*, *G. miocenica*, *G. tumida*, *G. sphericomiozea*, *Truncorotalia crassula* and thick walled globular planktonic foraminifera *Sphaeroidinellopsis seminulina*. Carinate planktonic foraminifera are indicative of water depths in excess of 100m were observed in deep water facies of the Korem and Wardo Formations.

4.19 Late Pliocene

Regression initiating in western New Guinea towards the end of the Early Pliocene (Fig. 5) resulted in more extensive and frequent shallow water areas interpreted across the region by the Late Pliocene (Fig. 29). This is supported by review of 64 wells and 29 outcrop samples. Deep water areas are interpreted based on the presence of globular and carinate planktonic foraminifera including *Globigerina* spp., *Globigerinoides* spp., *Globorotalia* spp., *Neogloboquadrina* spp., *Sphaeroidinella* spp. and *Sphaeroidinellopsis* spp. The distribution of relatively shallower areas are interpreted based on the presence of large flat rotaliines including *Cycloclypeus*, *Heterostegina* spp., *Operculina* spp. and typical back reef or lagoonal taxa such as soritid and miliolid foraminifera, coral, echinoids and bivalves.

4.20 Pleistocene

Early Pliocene relative sea-level fall continued into the Pleistocene and up to the present day in western New Guinea (Fig. 5). Several areas of the Bird's Head, Neck and Body were submerged beneath waters no greater than 50m. In the location of the present day islands of north of Cenderawasih Bay carbonate platforms deposited shallow water and reefal facies rocks of the coeval Mokmer and Manokwari Formations (Fig. 30). At this time Cenderawasih Bay itself became a distinct deep water feature filled by pelagic carbonates comprising planktonic foraminiferal packstones. Localised areas were subaerially exposed close to the Salawati and Bintuni basins (Fig. 30) as a precursor to the present day topography of the island of New Guinea.

Only five samples were collected of Pleistocene age (Fig. 30). Four samples representing the Mokmer Formation were located to the south-east of Biak and one sample from the Manokwari Formation of the north-eastern Bird's Head (Fig. 30). Palaeogeographic interpretations suggest a southwest directed deepening trend across a broad carbonate platform no deeper than 50m in water into the much deeper setting of Cenderawasih Bay (Fig. 30). The presence of a carbonate platform attaining these moderate water depths is indicated by common occurrences of the larger benthic foraminifera *Heterostegina* spp., and globular planktonic foraminifera including *Pulleniatina obliquiloculata* and *Globigerinoides quadrilobatus*. Rocks interpreted to have been deposited in reefal, shallow water settings up to 10m in depth comprise grainstones that contain abundant encrusting rodophyte red algae resilient to the brunt of high hydrodynamic energies. Behind this, quiet waters of the former back-reef are situated to the east of the island and contain delicate bryozoa and branching corals of the genera *Acropora* and *Porites*. Dasycladacean green algae, such as *Halimeda*, are also common. The disintegration of algal needles may contribute towards the large amount of micrite in wackestones deposited in this setting.

5. Conclusions

Biostratigraphy of well data and outcrop samples reveals a reasonably conformable sequence of sediments dated from the Silurian to present day. Two major transgressive-regressive cycles in relative sea-level are identified within the region (Fig. 5). Peaks in relative sea-level are interpreted to have occurred in the Late Cretaceous and Late Miocene (Fig. 5), with the latter tentatively correlated to the global Tor1 maximum flooding surface at 10.51 Ma where global sea-level was approximately 80m higher than today (Snedden and Liu, 2010; Gold et al., in review).

As the position of New Guinea position relative to Australia has not changed considerably since the Triassic (Gunawan et al., 2012), it is interpreted that our palaeogeographic reconstructions south of the Australia-Pacific suture from the Triassic onwards are relatively robust. Confidence in the robustness of the reconstructions using post-collisional stratigraphy of the region is also high. However, displacements along major strike-slip fault systems such as the Sorong Fault Zone, interpreted to have initiated in the Early Miocene (Visser and Hermes, 1962; Ali and Hall, 1995), may distort the reconstructions.

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Figure Captions

Figure 1. Structural map of western New Guinea. Faults were drawn based on features identified from ASTER digital elevation data, bathymetric multibeam and seismic data of the Biak and Cenderawasih Bay basins provided by TGS, and those encountered in the field. The offshore Manokwari Trough was drawn from GLORIA sonar imagery (after Milsom *et al.*, 1992). Derived regional stresses are implied after Bock *et al.* (2003), and vector of Pacific-Caroline plate motion plotted after Cloos *et al*. (2005).

Figure 2. Stratigraphy of the north and eastern Bird’s Head. Established from field data of this study and modified from Masria et al. (1981); Pieters et al. (1989); Robinson et al. (1990); Pieters et al. (1990); Brash et al. (1991).

Figure 3. Geological map of units encountered during this study. Distribution of geological units based on original GRDC maps and fieldwork from this study (Modified from Masria et al., 1981; Pieters et al., 1989; Robinson et al., 1990; Pieters et al., 1990)

Figure 4. The bathymetric boundaries used in the palaeogeographic reconstructions are derived from environmental preferences of foraminifera observed in this study. Thick lines indicate environments in which foraminifera are abundant, thin lines indicate environments in which they also occur infrequently. Environmental preferences are based on field data and Bé (1977), Hallock and Glenn (1986), van Gorsel (1988), Brash et al., 1991; BouDagher-Fadel (2008, 2015), Beavington-Penney and Racey (2004), Lunt (2013).

Figure 5. Relative sea-level curve based on the palaeogeographic reconstructions of an arbitrary data point in northern Bintuni Bay. Two main transgressive-regressive cycles are interpreted with peak relative sea-level occurring during the Late Cretaceous and Late Miocene.

Figure 6. Palaeogeographic reconstruction of western New Guinea during the Silurian. Based on evidence from Silurian aged sediments encountered in 1 well and distribution of the Kemum and Aisasjur Formations, and Modio Dolomite.

Figure 7. Palaeogeographic reconstruction of western New Guinea during the Carboniferous. Based on evidence from Carboniferous aged sediments encountered in 2 wells and distribution of Aifam Group sediments.

Figure 8. Palaeogeographic reconstruction of western New Guinea during the Permian. Based on evidence from Permian aged sediments encountered in 24 wells and distribution of Aifam Group sediments.

Figure 9. Palaeogeographic reconstruction of western New Guinea during the Triassic. Based on evidence from Triassic aged sediments encountered in 13 wells and distribution of the Tipuma Formation.

Figure 10. Palaeogeographic reconstruction of western New Guinea during the Early Jurassic. Based on evidence from Early Jurassic aged sediments encountered in 2 wells and distribution of the Tipuma Formation.

Figure 11. Palaeogeographic reconstruction of western New Guinea during the Middle Jurassic. Based on evidence from Middle Jurassic aged sediments encountered in 25 wells, 8 outcrop samples and distribution of the Kopai and Tamrau Formations.

Figure 12. Bathonian-Callovian aged ammonites collected from the Kopai Formation close to the village of Wendesi. A) *Macrocephalites keeuwensis*, B) *Sphaeroceras boehmi* and C) *Holcophylloceras indicum*

Figure 13. Palaeogeographic reconstruction of western New Guinea during the Late Jurassic. Based on evidence from Late Jurassic aged sediments encountered in 26 wells and distribution of the Kopai, Tamrau, Woniwogi, Demu and Lelinta Formations.

Figure 14. Palaeogeographic reconstruction of western New Guinea during the Early Cretaceous. Based on evidence from Early Cretaceous aged sediments encountered in 10 wells and distribution of the Tamrau, Woniwogi, Jass, demu and Lelinta Formations, and Piniya Mudstone.

Figure 15. Palaeogeographic reconstruction of western New Guinea during the Late Cretaceous. Based on evidence from Late Cretaceous aged sediments encountered in 40 wells, 6 outcrop samples and distribution of the Tamrau and Jass formations, Amiri and Ekmai Sandstones, Piniya Mudstone, Imskin Limestone and Korido Metamorphics.

Figure 16. Age-diagnostic Late Cretaceous planktonic foraminifera, and key palaeoenvironmental indicators, observed in outcrop samples. A-D) Carinate morphologies indicative of water depths greater than 100m. E-F) Globular planktonic foraminifera. Key - *Globotruncana* spp.(G), *Globotruncanita conica* (*G.c*), *Globotruncana arca* (*G.a*), *Abathomphalus mayaroensis* (*A.m*), *Heterohelix* spp. (*H*).

Figure 17. Palaeogeographic reconstruction of western New Guinea during the Paleocene. Based on evidence from Paleocene aged sediments encountered in 30

wells, 5 outcrop samples and distribution of the Waripi and Daram Formations, and Imskin Limestone.

Figure 18. Palaeogeographic reconstruction of western New Guinea during the Early Eocene. Based on evidence from Early Eocene aged sediments encountered in 25 wells, 9 outcrop samples and distribution of the Faumai, Imskin and Lengguru Limestones.

Figure 19. Age-diagnostic Early Eocene foraminifera, and key palaeoenvironmental indicators, observed in outcrop samples. A-E) Large, flat, rotaliine foraminifera indicative of water depths between 20m and 50m from the Faumai Limestone. F) Globular planktonic foraminifera indicative of water depths between 50m and 100m, Imskin limestone. G-H) Deep-water facies containing carinate planktonic foraminifera indicative of water depths in excess of 100m, Imskin Limestone. Key - *Alveolina* spp. (*A*), *Asterocyclina* spp. (*As*), *Alveolina subpyrenaica* (*A.s*), *Discocyclina ranikotensis* (*D.r*), *Alveolina globosa* (*A.g*), *Operculina* spp. (*O*), *Cuvillierina* spp. (*C*), *Acarinina* spp. (*Ac*), *Globigerinatheka* spp. (*Gt*), *Morozovella* spp. (*Mz*).

Figure 20. Palaeogeographic reconstruction of western New Guinea during the Middle - Late Eocene. Based on evidence from Middle - Late Eocene aged sediments encountered in 39 wells, 13 outcrop samples and distribution of the Faumai, Imskin and Lengguru Limestones, and Auwewa Formation.

Figure 21. Age-diagnostic Middle – Late Eocene foraminifera, and key palaeoenvironmental indicators, observed in outcrop samples. A-B) Shallow water

facies from the Faumai Limestone. C-D) Shallow water facies observed in limestone lenses of the Auwewa Formation from Supiori. E-G) Globular planktonic foraminifera indicative of water depths between 50m and 100m, Imskin Limestone. H) Deep-water facies containing carinate planktonic foraminifera indicative of water depths greater than 100m, Imskin Limestone. Key – *Nummulites gizehensis* (*N.g*), *Pellatispirella* spp. (*Pt*), *Acarinina* spp. (*Ac*), *Globigerinatheka* spp. (*Gt*), *Subbotina* spp. (*Sb*), *Morozovella* spp. (*Mz*).

Figure 22. Palaeogeographic reconstruction of western New Guinea during the Oligocene. Based on evidence from Oligocene aged sediments encountered in 25 wells, 6 outcrop samples and distribution of the Sirga Formation.

Figure 23. Palaeogeographic reconstruction of western New Guinea during the Early Miocene. Based on evidence from Early Miocene aged sediments encountered in 48 wells, 37 outcrop samples and distribution of the Koor, Kais and Maruni Limestones, and Wainukendi, Wafordori and Wurui Formations.

Figure 24. Age-diagnostic Early Miocene foraminifera, and key palaeoenvironmental indicators, observed in outcrop samples. A-D) Shallow water, reefal, grainstones of the Maruni Limestone. E) Shallow water packstone of the Kais Limestone. F) Large, flat, rotaliines indicate water depths between 20m and 50m in the Maruni Limestone. Key – *Lepidocyclina sumatrensis* (*L.s*), *Lepidocyclina brouweri* (*L.b*), *Lepidocyclina oneatensis* (*L.o*), *Miogypsina tani* (*M.t*), *Spiroclypeus tidoenganensis* (*S.t*), *Eulepidina* spp. (*Eu*), *Miogypsina* spp. (*Mg*), *Amphistegina* spp. (*Am*), *Heterostegina* spp. (*Hs*).

Figure 25. Palaeogeographic reconstruction of western New Guinea during the Middle Miocene. Based on evidence from Middle Miocene aged sediments encountered in 55 wells, 42 outcrop samples and distribution of the Koor, Kais and Maruni Limestones, and Wainukendi, Wafordori and Napisendi Formations, and Sumboi Marl.

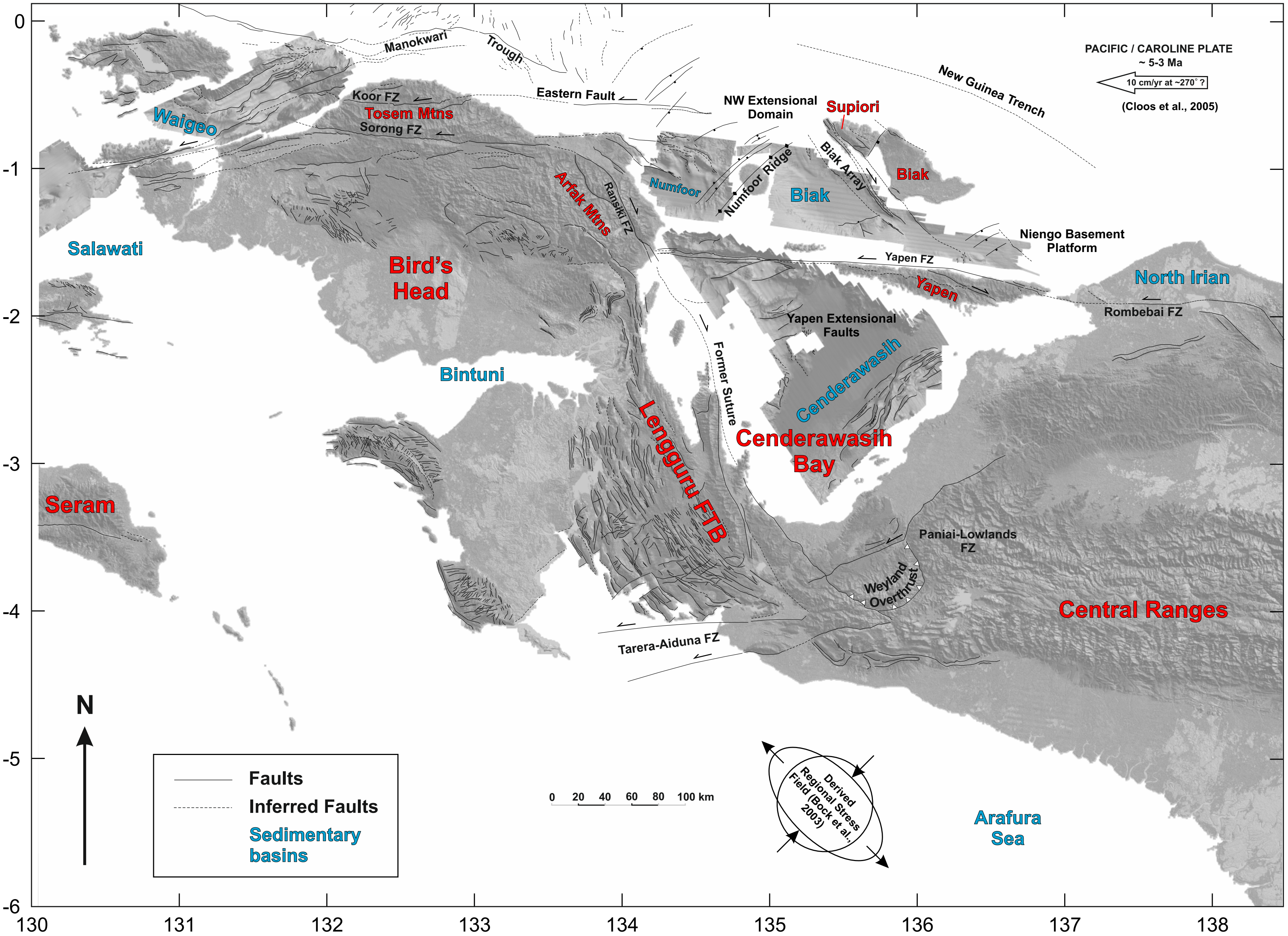
Figure 26. Age-diagnostic Middle Miocene foraminifera, and key palaeoenvironmental indicators, observed in outcrop samples. A) Large, flat, rotaliines indicating water depths between 20m and 50m from the Maruni Limestone. B) Shallow water wackestone containing taxa indicative of water depths no greater than 20m. C-D) Globular planktonic foraminifera indicating water depths between 50m and 100m from near the top of the Maruni Limestone. Key – *Katacycloclypeus annulatus* (*K.a*), *Borelis melo* (*B.m*), *Globigerinoides* spp. (*Gd*), *Orbulina universa* (*O.u*).

Figure 27. Palaeogeographic reconstruction of western New Guinea during the Late Miocene. Based on evidence from Late Miocene aged sediments encountered in 65 wells, 24 outcrop samples and distribution of the Klasafet and Befoor Formations.

Figure 28. Palaeogeographic reconstruction of western New Guinea during the Early Pliocene. Based on evidence from Early Pliocene aged sediments encountered in 66 wells, 29 outcrop samples and distribution of the Klasman, Opmorai, Befoor, Wardo, Korem and Kurudu Formations, and the Wai Limestone.

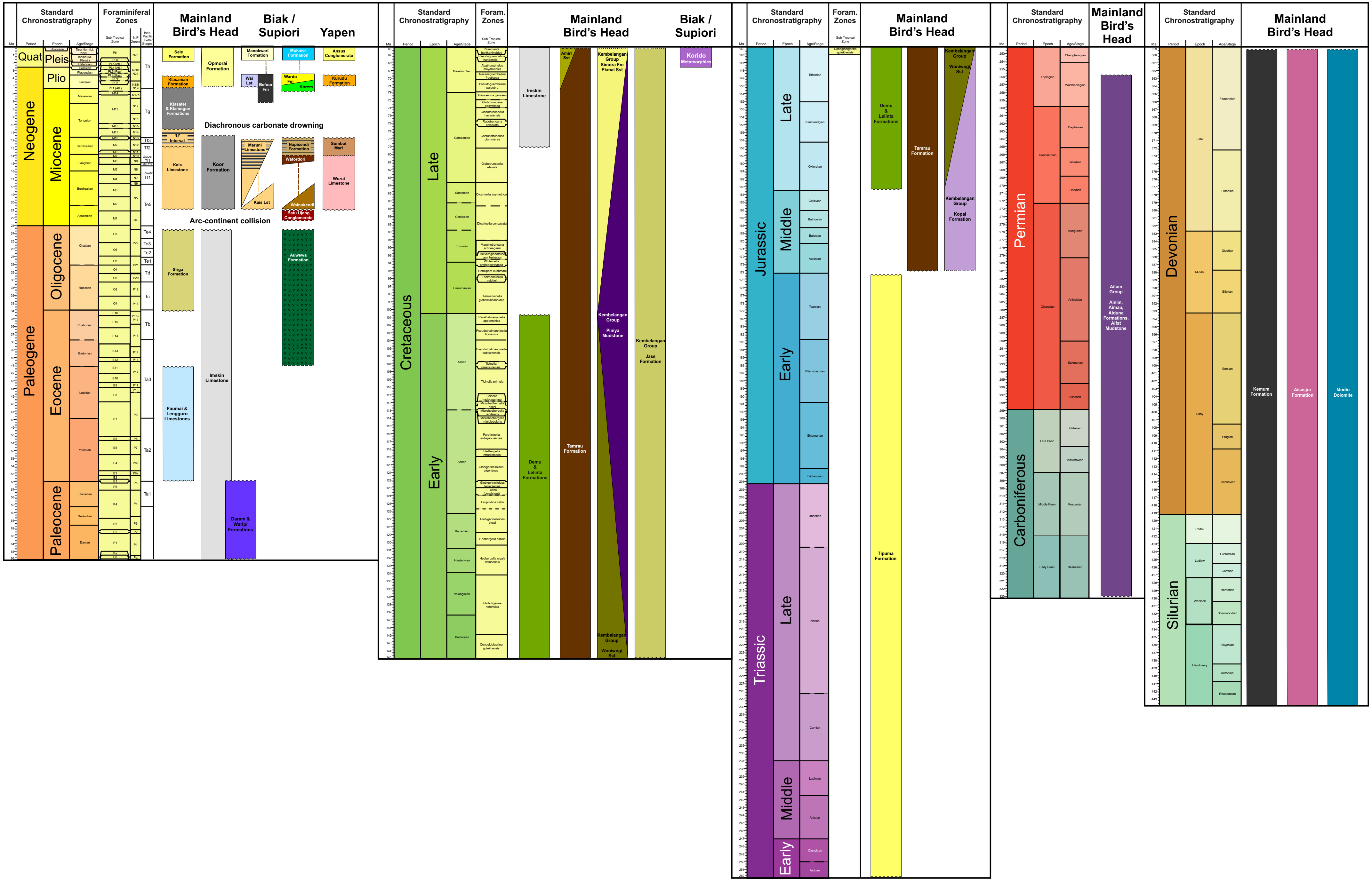
Figure 29. Palaeogeographic reconstruction of western New Guinea during the Late Pliocene. Based on evidence from Late Pliocene aged sediments encountered in 62 wells, 29 outcrop samples and distribution of the Opmorai Formation.

Figure 30. Palaeogeographic reconstruction of western New Guinea during the Pleistocene. Based on evidence from Pleistocene aged sediments encountered in 44 wells, 5 outcrop samples and distribution of the Sele, Opmorai, Manokwari and Mokmer Formations, and Ansus Conglomerate.



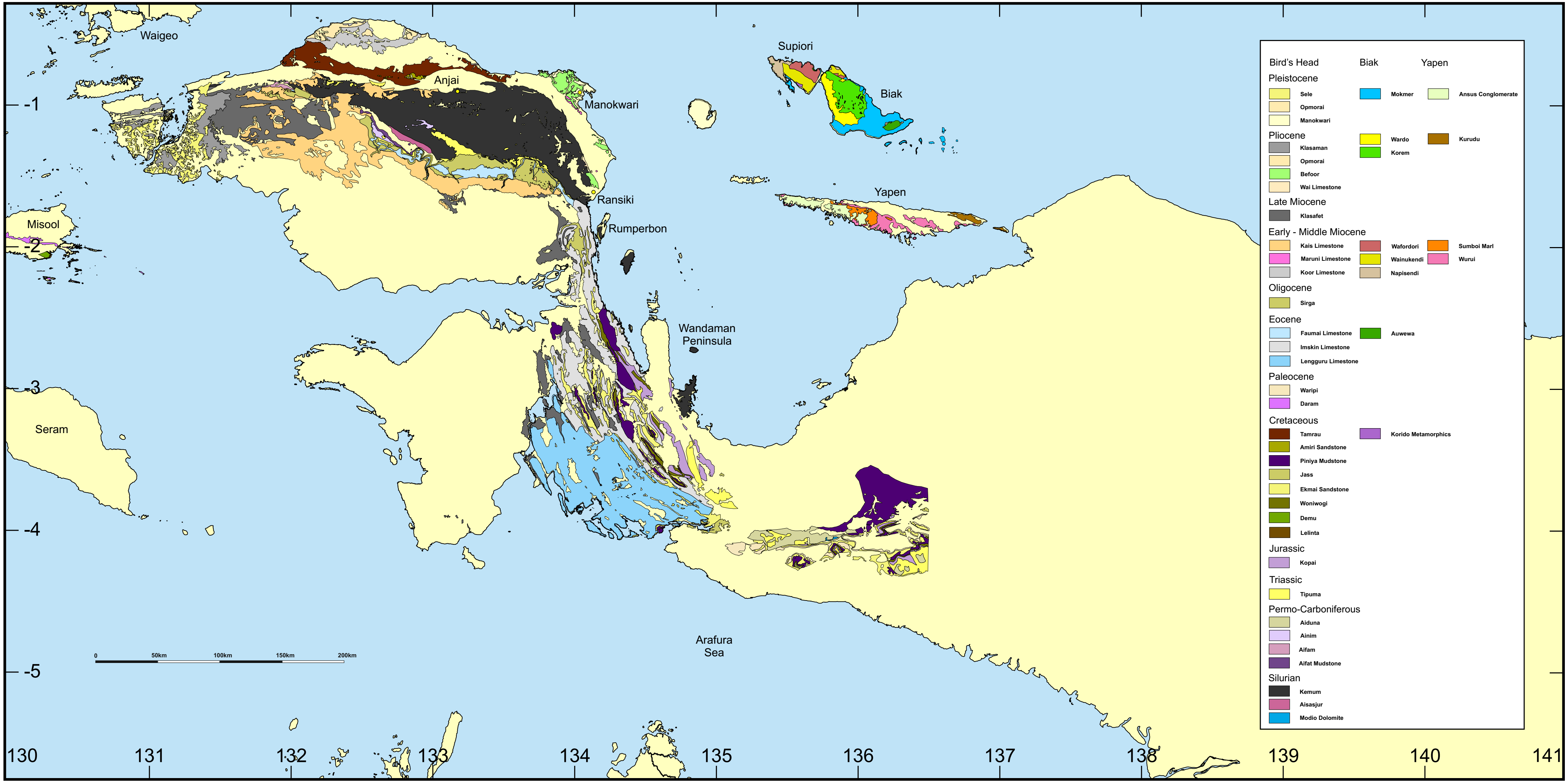
PACIFIC / CAROLINE PLATE
~ 5-3 Ma
10 cm/yr at ~270° ?
(Cloos et al., 2005)
Manokwari
Trough
New Guinea Trench
Eastern Fault
Koor FZ
Tosem Mtns
Sorong FZ
Waigeo
NW Extensional Domain
Supiori
Biak
Numfoor
Numfoor Ridge
Biak Array
Arfak Mtns
Ransiki FZ
Salawati
Bird's Head
Niengo Basement Platform
Yapen FZ
Yapen
North Irian
Rombebai FZ
Yapen Extensional Faults
Former Suture
Cenderawasih
Bintuni
Lengguru FTB
Cenderawasih Bay
Seram
Paniai-Lowlands FZ
Weyland Overthrust
Central Ranges
Tarera-Aiduna FZ
N
Faults
Inferred Faults
Sedimentary basins
0 20 40 60 80 100 km
Derived Regional Stress Field (Bock et al., 2003)
Arafura Sea
0
-1
-2
-3
-4
-5
-6
130
131
132
133
134
135
136
137
138

Figure 1



Standard Chronostratigraphy
Foraminiferal Zones
Mainland Bird's Head
Biak / Supiori
Yapen
Diachronous carbonate drowning
Arc-continent collision
Neogene
Paleogene
Miocene
Oligocene
Eocene
Paleocene
Cretaceous
Late
Early
Jurassic
Middle
Triassic
Permian
Carboniferous
Devonian
Silurian
Mainland Bird's Head
Kembelangan Group
Tamrau Formation
Tipuma Formation
Aifam Group
Kemum Formation
Aisasjur Formation
Modio Dolomite

Figure 2



Waigeo
Anjai
Manokwari
Supiori
Biak
Yapen
Misool
Ransiki
Rumperbon
Wandaman
Peninsula
Seram
Arafura
Sea
0
50km
100km
150km
200km
-1
-2
-3
-4
-5
130
131
132
133
134
135
136
137
138
139
140
141
Bird's Head
Biak
Yapen
Pleistocene
Sele
Opmorai
Manokwari
Mokmer
Ansus Conglomerate
Pliocene
Klasaman
Opmorai
Befoor
Wai Limestone
Wardo
Korem
Kurudu
Late Miocene
Klasafet
Early - Middle Miocene
Kais Limestone
Maruni Limestone
Koor Limestone
Wafordori
Wainukendi
Napisendi
Sumboi Marl
Wurui
Oligocene
Sirga
Eocene
Faumai Limestone
Imskin Limestone
Lengguru Limestone
Auwewa
Paleocene
Waripi
Daram
Cretaceous
Tamrau
Amiri Sandstone
Piniya Mudstone
Jass
Ekmai Sandstone
Woniwogi
Demu
Lelinta
Korido Metamorphics
Jurassic
Kopai
Triassic
Tipuma
Permo-Carboniferous
Aiduna
Ainim
Aifam
Aifat Mudstone
Silurian
Kemum
Aisasjur
Modio Dolomite

Figure 3

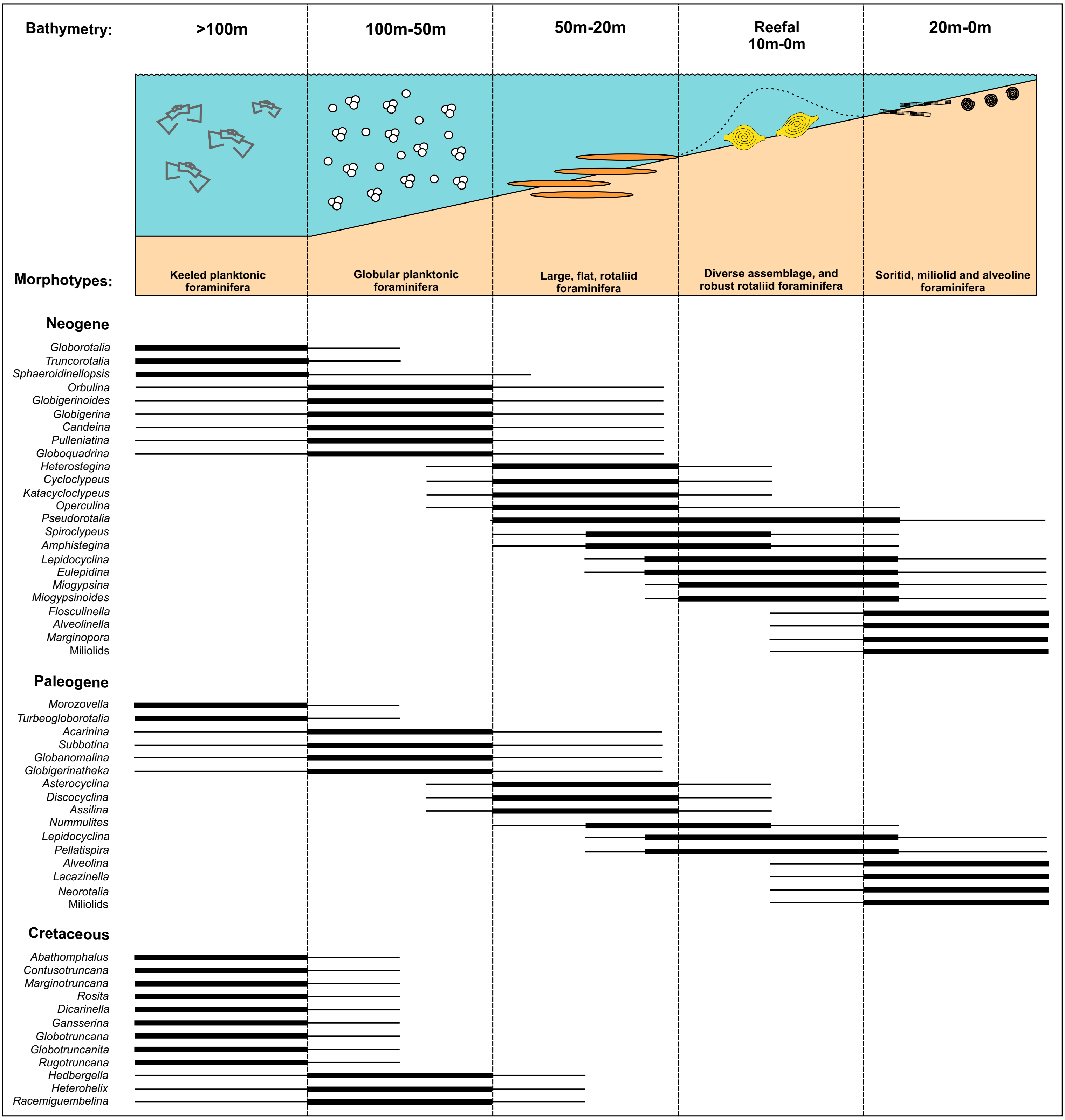

Bathymetry:
>100m
100m-50m
50m-20m
Reefal 10m-0m
20m-0m
Morphotypes:
Keeled planktonic foraminifera
Globular planktonic foraminifera
Large, flat, rotaliid foraminifera
Diverse assemblage, and robust rotaliid foraminifera
Soritid, miliolid and alveoline foraminifera
Neogene
Globorotalia
Truncorotalia
Sphaeroidinellopsis
Orbulina
Globigerinoides
Globigerina
Candeina
Pulleniatina
Globoquadrina
Heterostegina
Cycloclypeus
Katacycloclypeus
Operculina
Pseudorotalia
Spiroclypeus
Amphistegina
Lepidocyclina
Eulepidina
Miogypsina
Miogypsinoides
Flosculinella
Alveolinella
Marginopora
Miliolids
Paleogene
Morozovella
Turbeogloborotalia
Acarinina
Subbotina
Globanomalina
Globigerinatheka
Asterocyclina
Discocyclina
Assilina
Nummulites
Lepidocyclina
Pellatispira
Alveolina
Lacazinella
Neorotalia
Miliolids
Cretaceous
Abathomphalus
Contusotruncana
Marginotruncana
Rosita
Dicarinella
Gansserina
Globotruncana
Globotruncanita
Rugotruncana
Hedbergella
Heterohelix
Racemiguembelina

Figure 4

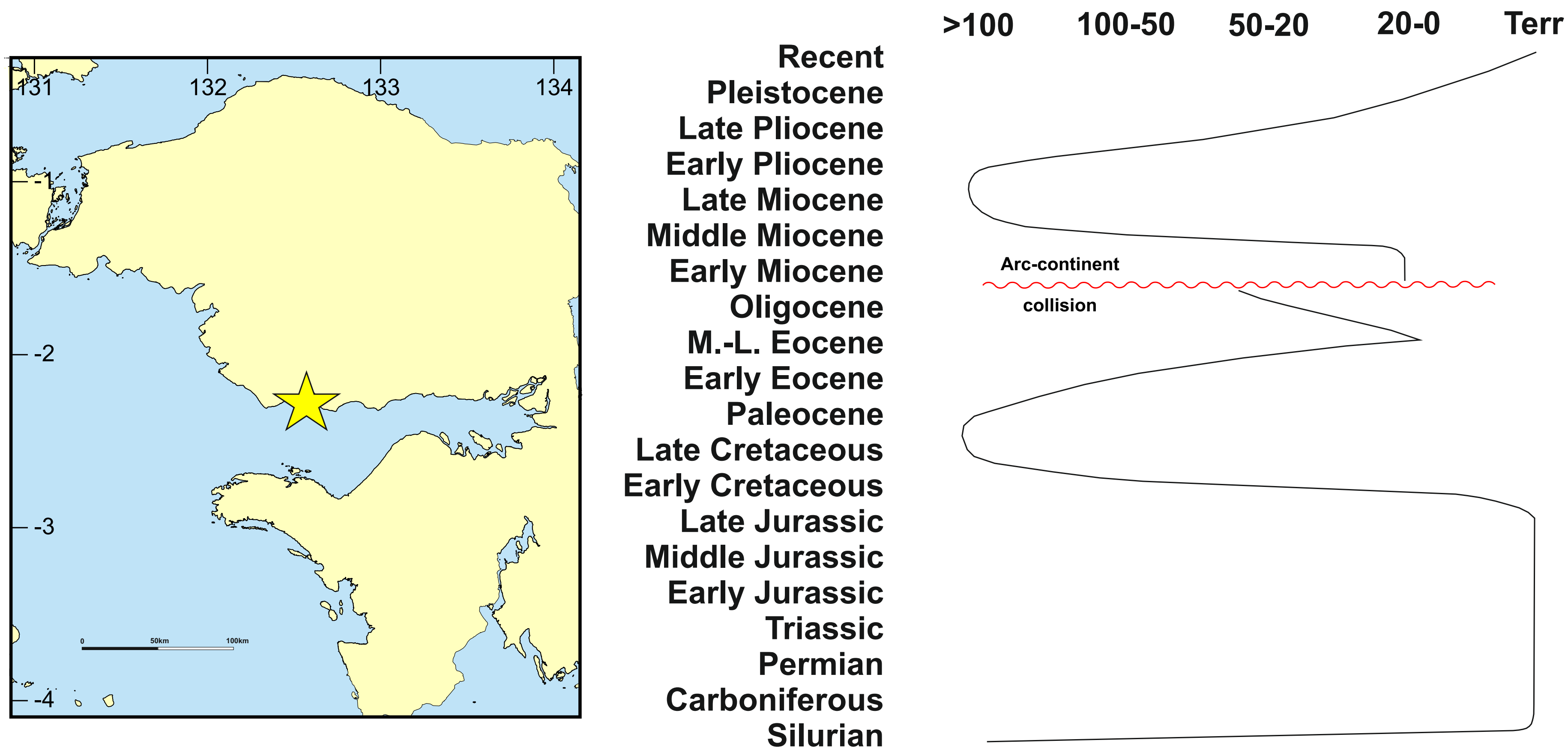
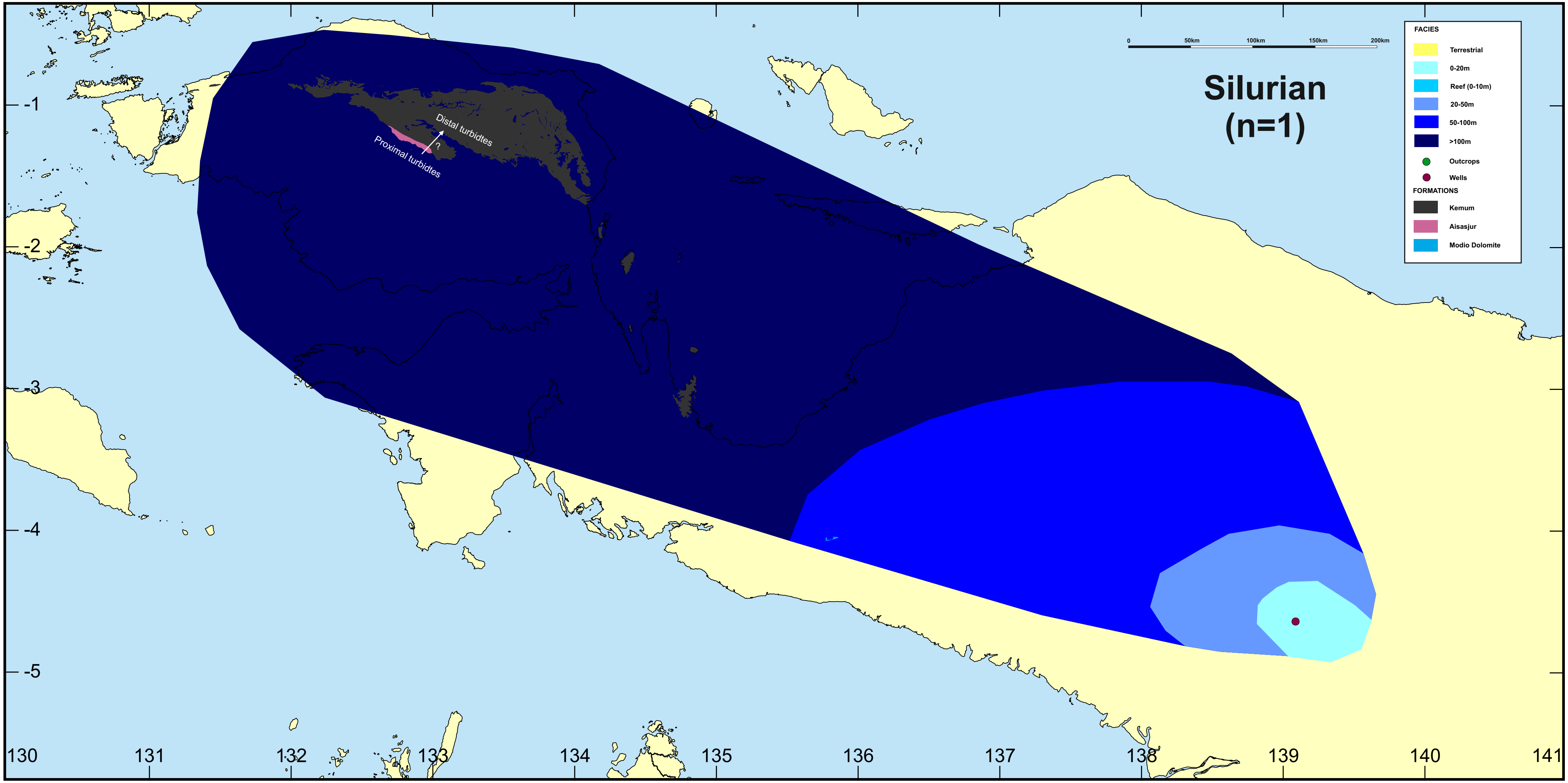

131
132
133
134
-2
-3
-4
0
50km
100km
>100
100-50
50-20
20-0
Terr
Recent
Pleistocene
Late Pliocene
Early Pliocene
Late Miocene
Middle Miocene
Early Miocene
Oligocene
M.-L. Eocene
Early Eocene
Paleocene
Late Cretaceous
Early Cretaceous
Late Jurassic
Middle Jurassic
Early Jurassic
Triassic
Permian
Carboniferous
Silurian
Arc-continent
collision

Figure 5



Silurian
(n=1)
0
50km
100km
150km
200km
FACIES
Terrestrial
0-20m
Reef (0-10m)
20-50m
50-100m
>100m
Outcrops
Wells
FORMATIONS
Kemum
Aisasjur
Modio Dolomite
Distal turbidtes
Proximal turbidtes
?
-1
-2
-3
-4
-5
130
131
132
133
134
135
136
137
138
139
140
141

Figure 6

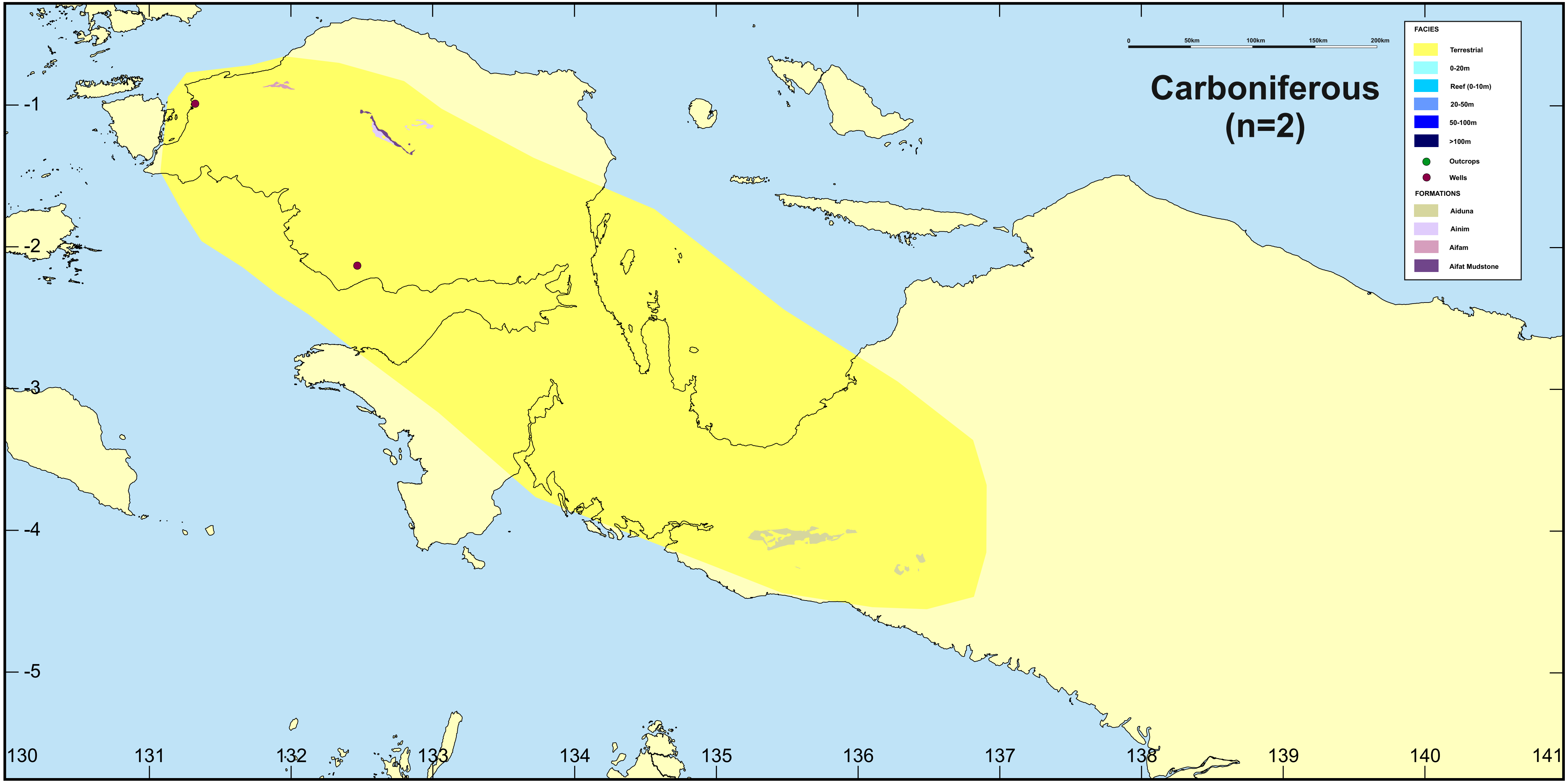

Carboniferous
(n=2)
0
50km
100km
150km
200km
FACIES
Terrestrial
0-20m
Reef (0-10m)
20-50m
50-100m
>100m
Outcrops
Wells
FORMATIONS
Aiduna
Ainim
Aifam
Aifat Mudstone
-1
-2
-3
-4
-5
130
131
132
133
134
135
136
137
138
139
140
141

Figure 7

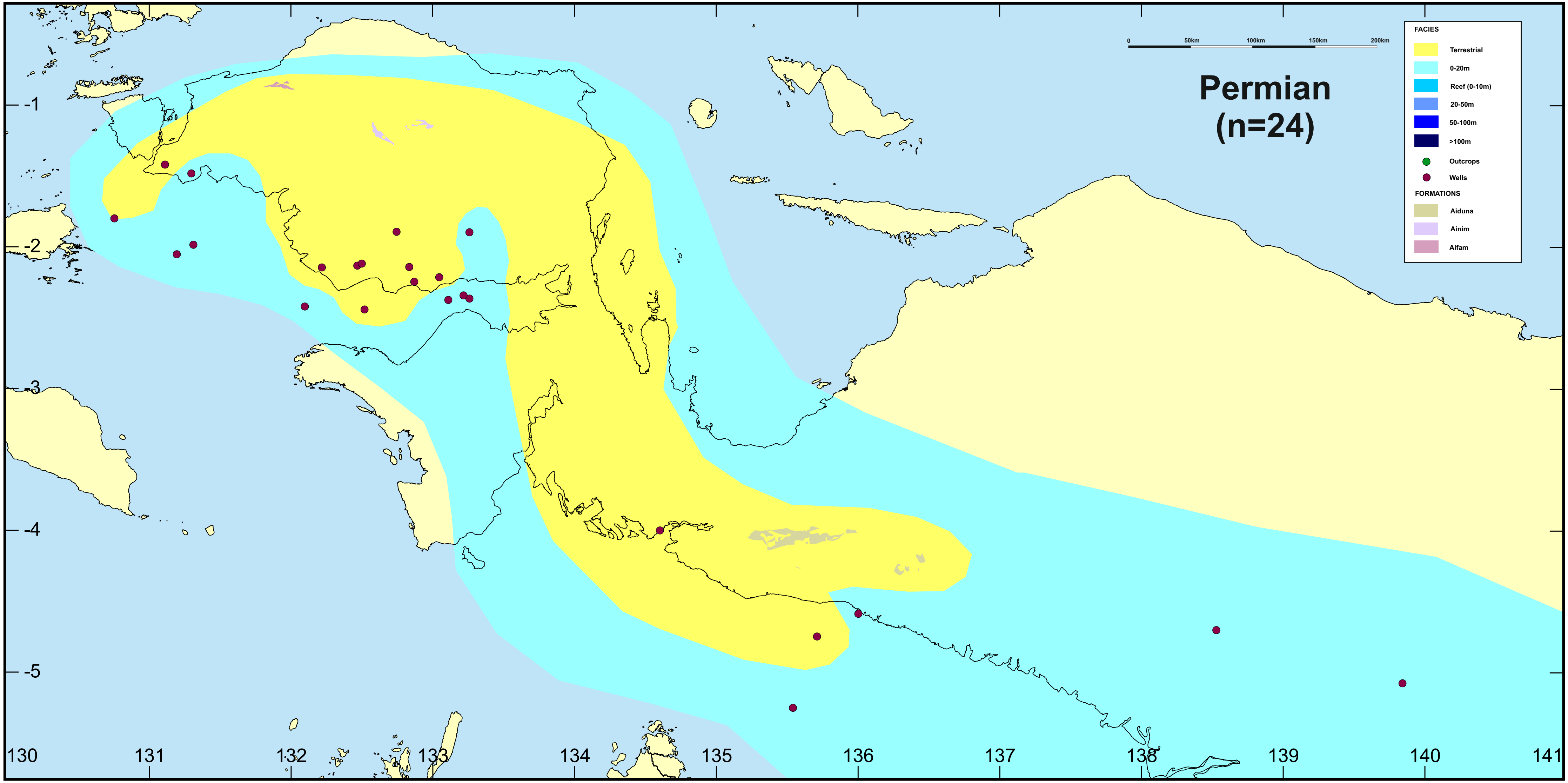

Permian
(n=24)
FACIES
Terrestrial
0-20m
Reef (0-10m)
20-50m
50-100m
>100m
Outcrops
Wells
FORMATIONS
Aiduna
Ainim
Aifam
0
50km
100km
150km
200km
-1
-2
-3
-4
-5
130
131
132
133
134
135
136
137
138
139
140
141

Figure 8

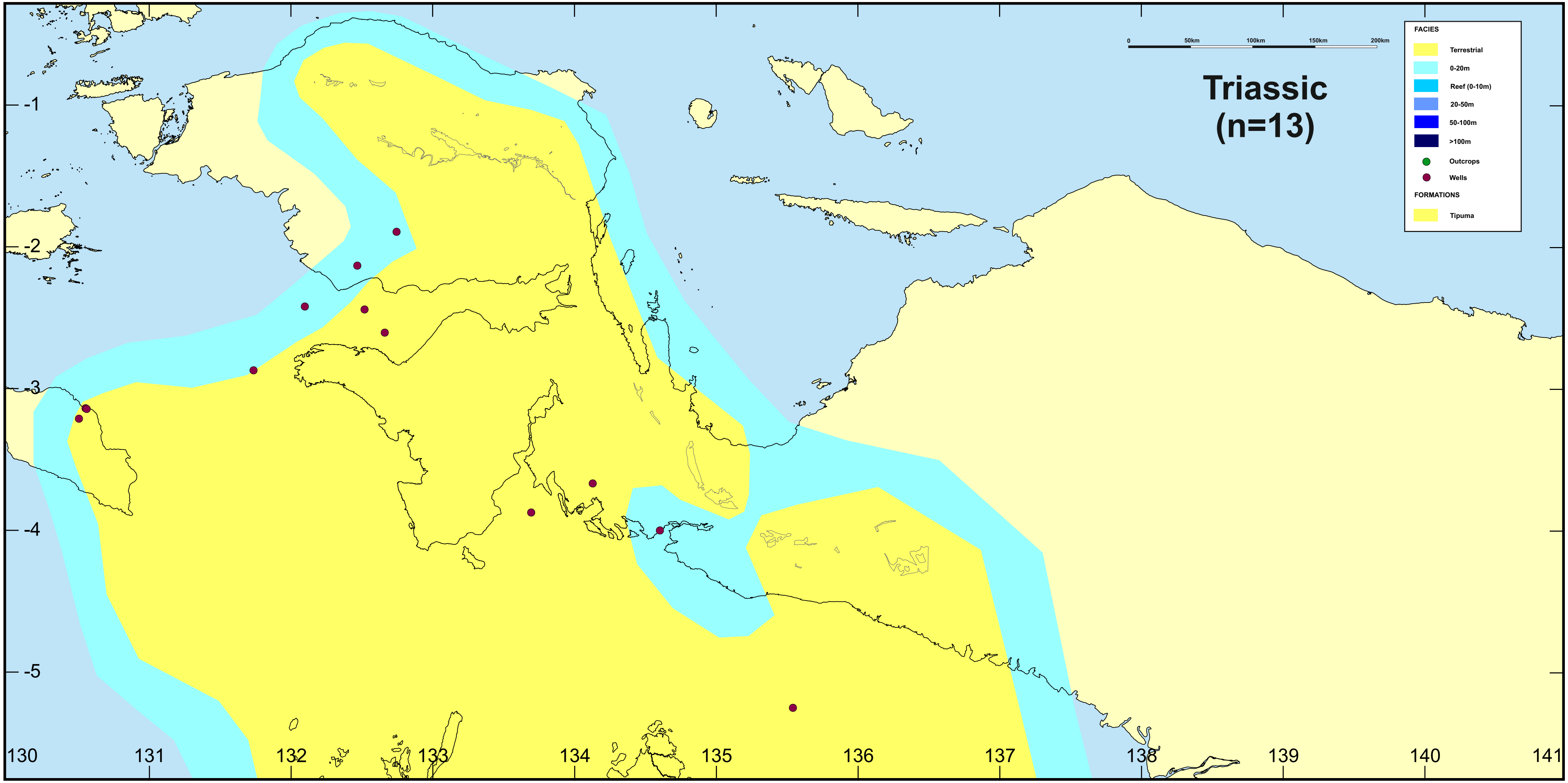

Triassic
(n=13)
FACIES
Terrestrial
0-20m
Reef (0-10m)
20-50m
50-100m
>100m
Outcrops
Wells
FORMATIONS
Tipuma
0
50km
100km
150km
200km
-1
-2
-3
-4
-5
130
131
132
133
134
135
136
137
138
139
140
141

Figure 9

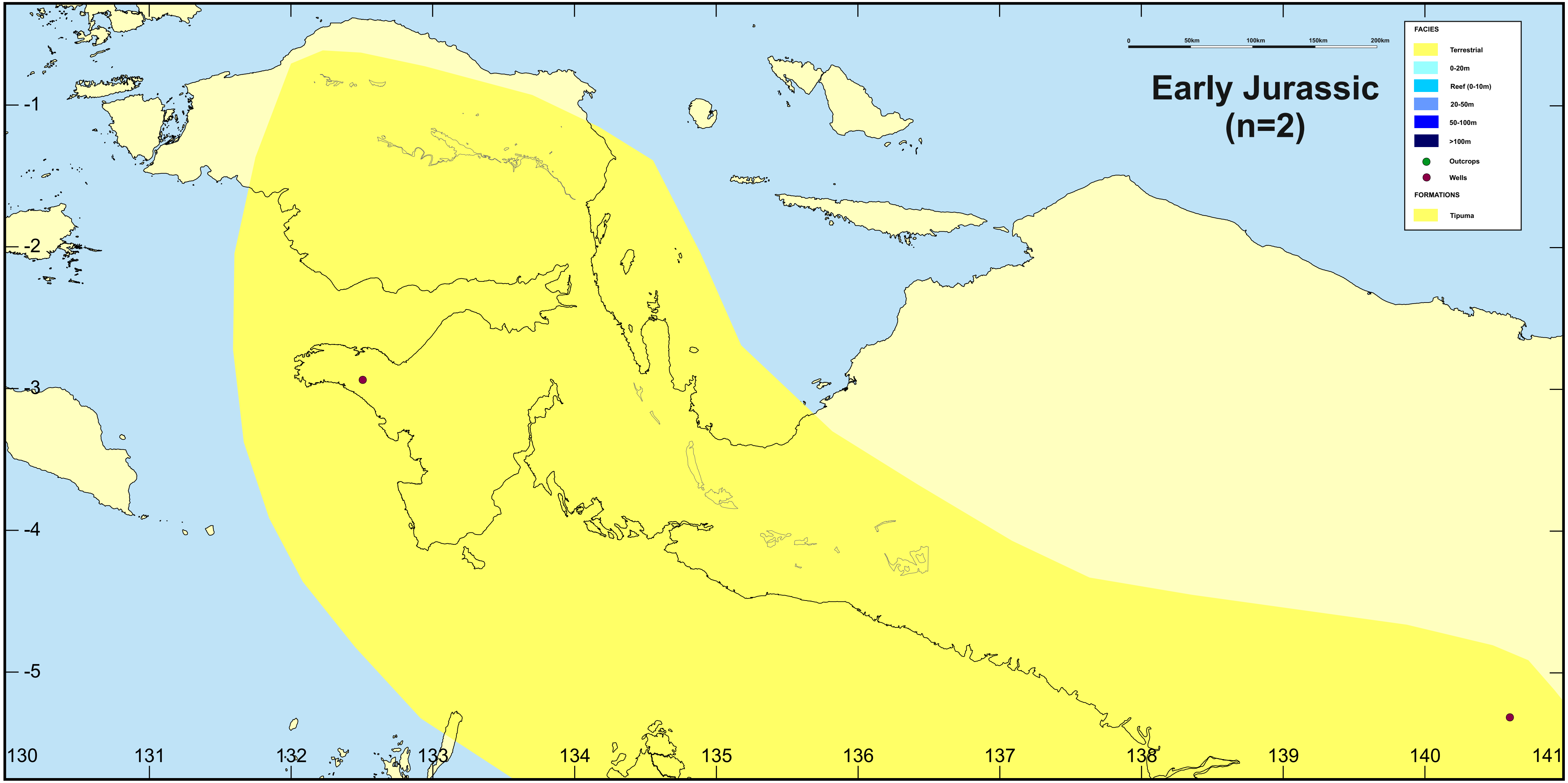
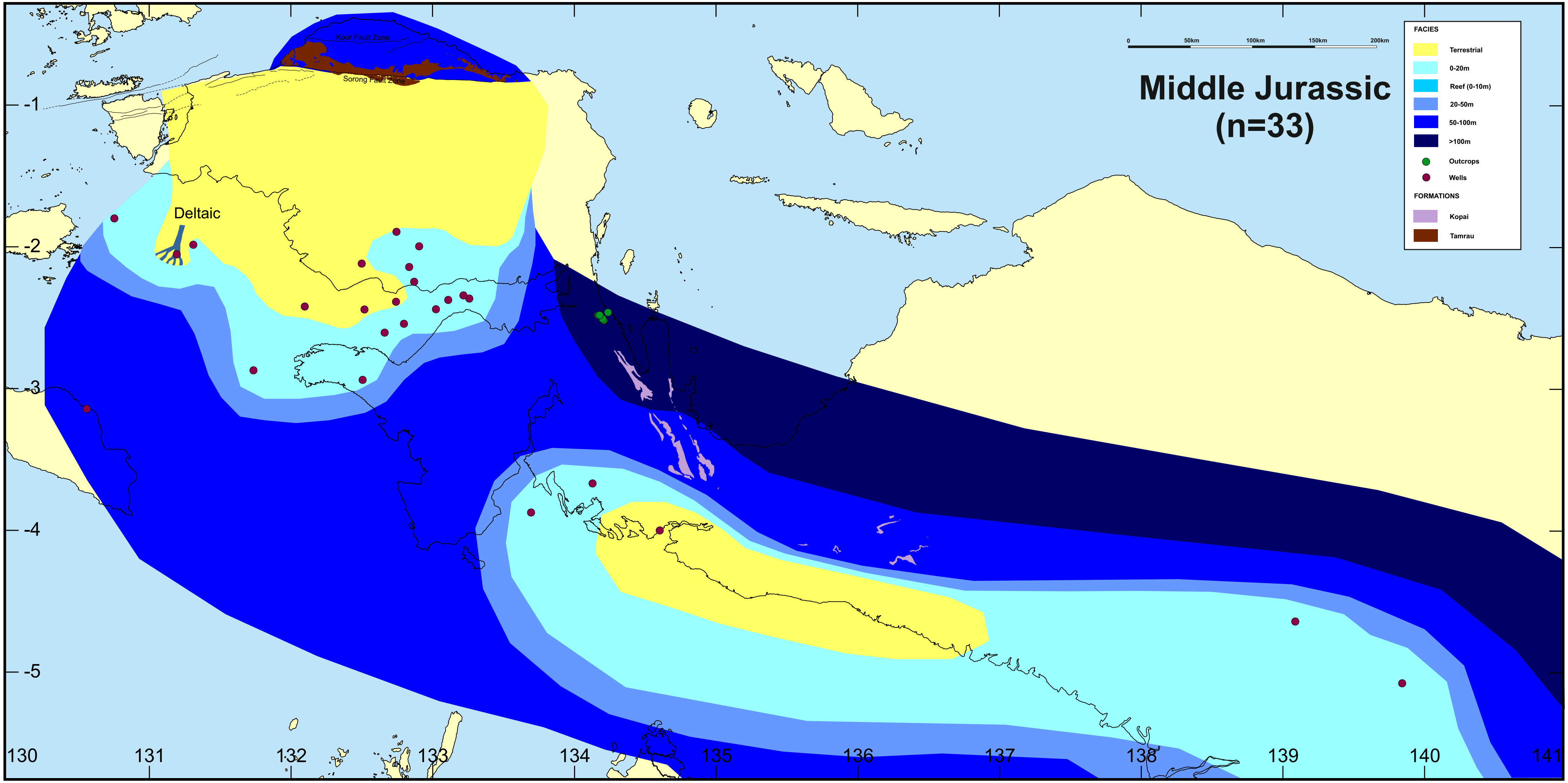

Early Jurassic
(n=2)
0
50km
100km
150km
200km
FACIES
Terrestrial
0-20m
Reef (0-10m)
20-50m
50-100m
>100m
Outcrops
Wells
FORMATIONS
Tipuma
-1
-2
-3
-4
-5
130
131
132
133
134
135
136
137
138
139
140
141

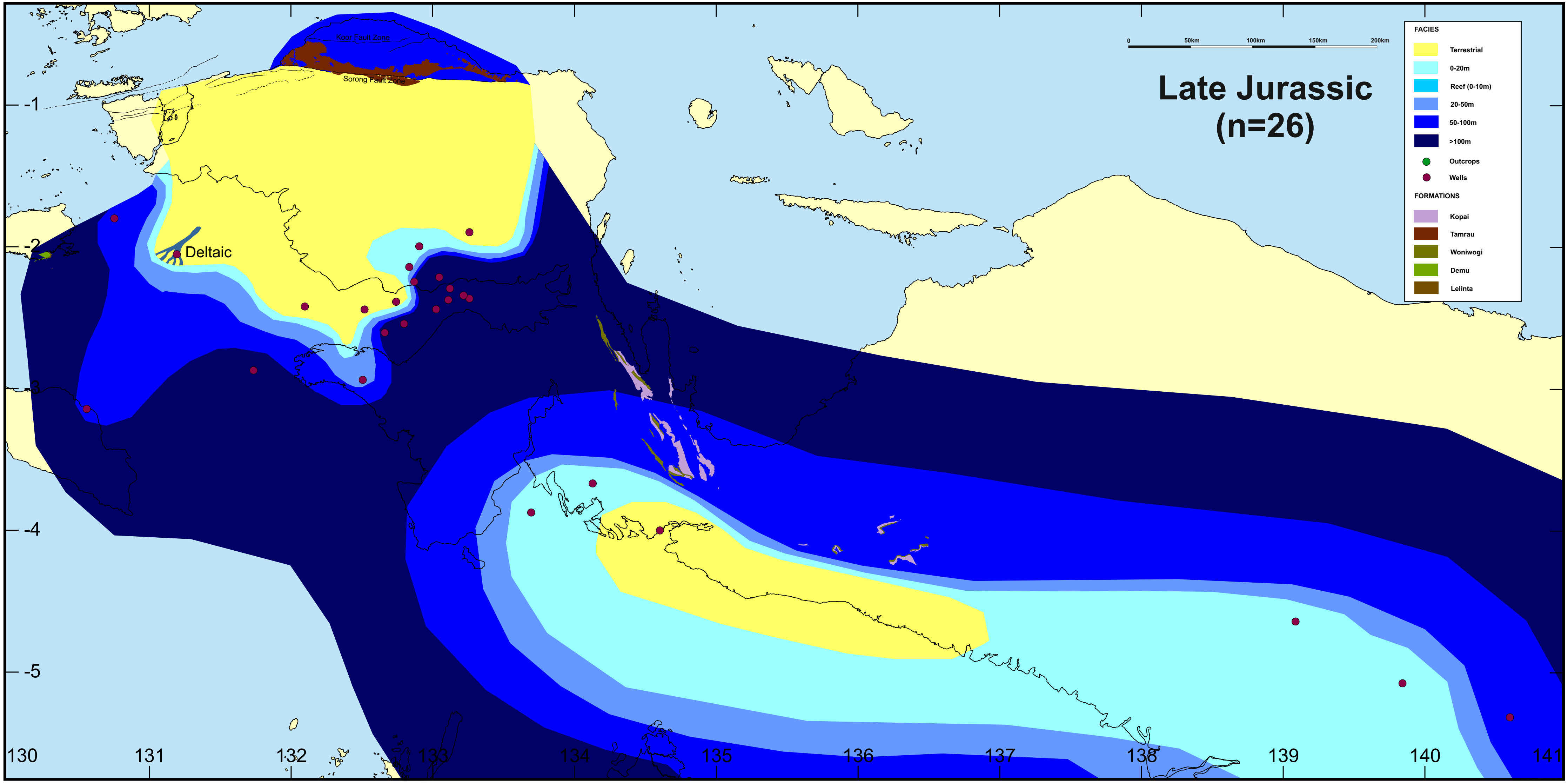
Figure 10



Middle Jurassic
(n=33)
FACIES
Terrestrial
0-20m
Reef (0-10m)
20-50m
50-100m
>100m
Outcrops
Wells
FORMATIONS
Kopai
Tamrau
0
50km
100km
150km
200km
Deltaic
Koor Fault Zone
Sorong Fault Zone
-1
-2
-3
-4
-5
130
131
132
133
134
135
136
137
138
139
140
141

Figure 11

Figure 12



Late Jurassic
(n=26)
0
50km
100km
150km
200km
FACIES
Terrestrial
0-20m
Reef (0-10m)
20-50m
50-100m
>100m
Outcrops
Wells
FORMATIONS
Kopai
Tamrau
Woniwogi
Demu
Lelinta
Koor Fault Zone
Sorong Fault Zone
Deltaic
-1
-2
-3
-4
-5
130
131
132
133
134
135
136
137
138
139
140
141

Figure 13

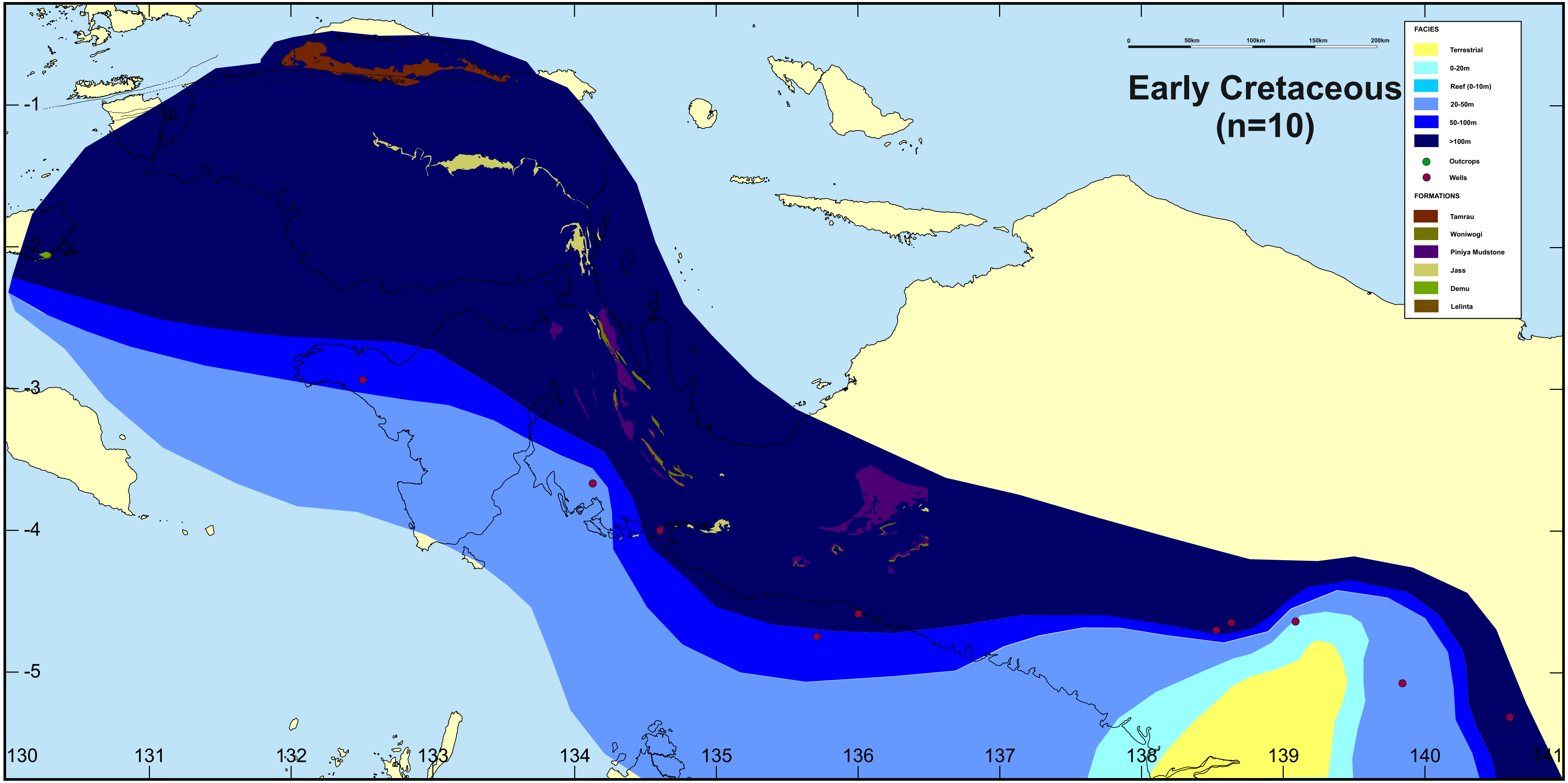
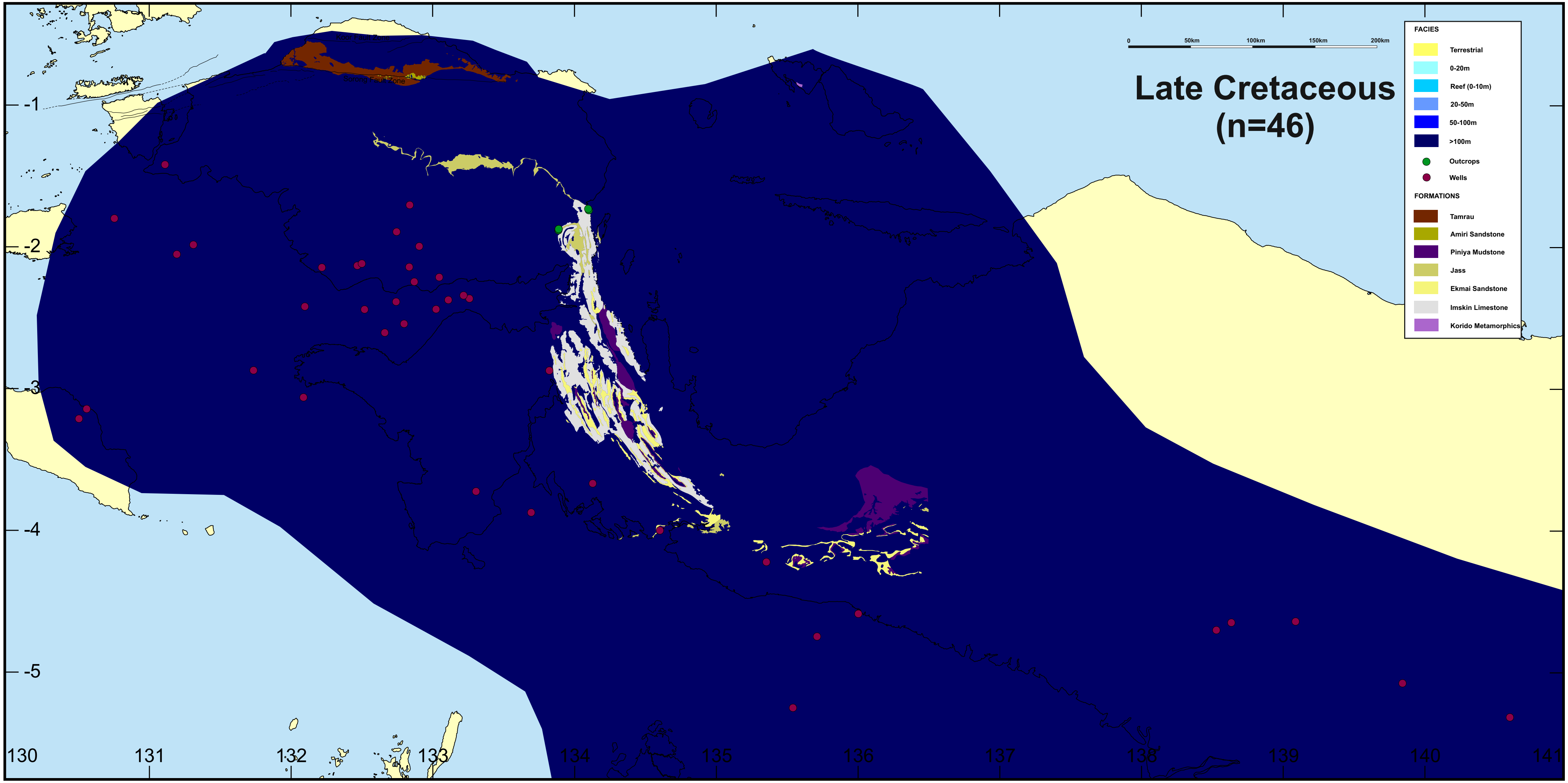

Early Cretaceous
(n=10)
FACIES
Terrestrial
0-20m
Reef (0-10m)
20-50m
50-100m
>100m
Outcrops
Wells
FORMATIONS
Tamrau
Woniwogi
Piniya Mudstone
Jass
Demu
Lelinta
0
50km
100km
150km
200km
-1
-2
-3
-4
-5
130
131
132
133
134
135
136
137
138
139
140
141

Figure 14



Late Cretaceous
(n=46)
0
50km
100km
150km
200km
FACIES
Terrestrial
0-20m
Reef (0-10m)
20-50m
50-100m
>100m
Outcrops
Wells
FORMATIONS
Tamrau
Amiri Sandstone
Piniya Mudstone
Jass
Ekmai Sandstone
Imskin Limestone
Korido Metamorphics
Koor Fault Zone
Sorong Fault Zone
-1
-2
-3
-4
-5
130
131
132
133
134
135
136
137
138
139
140
141

Figure 15

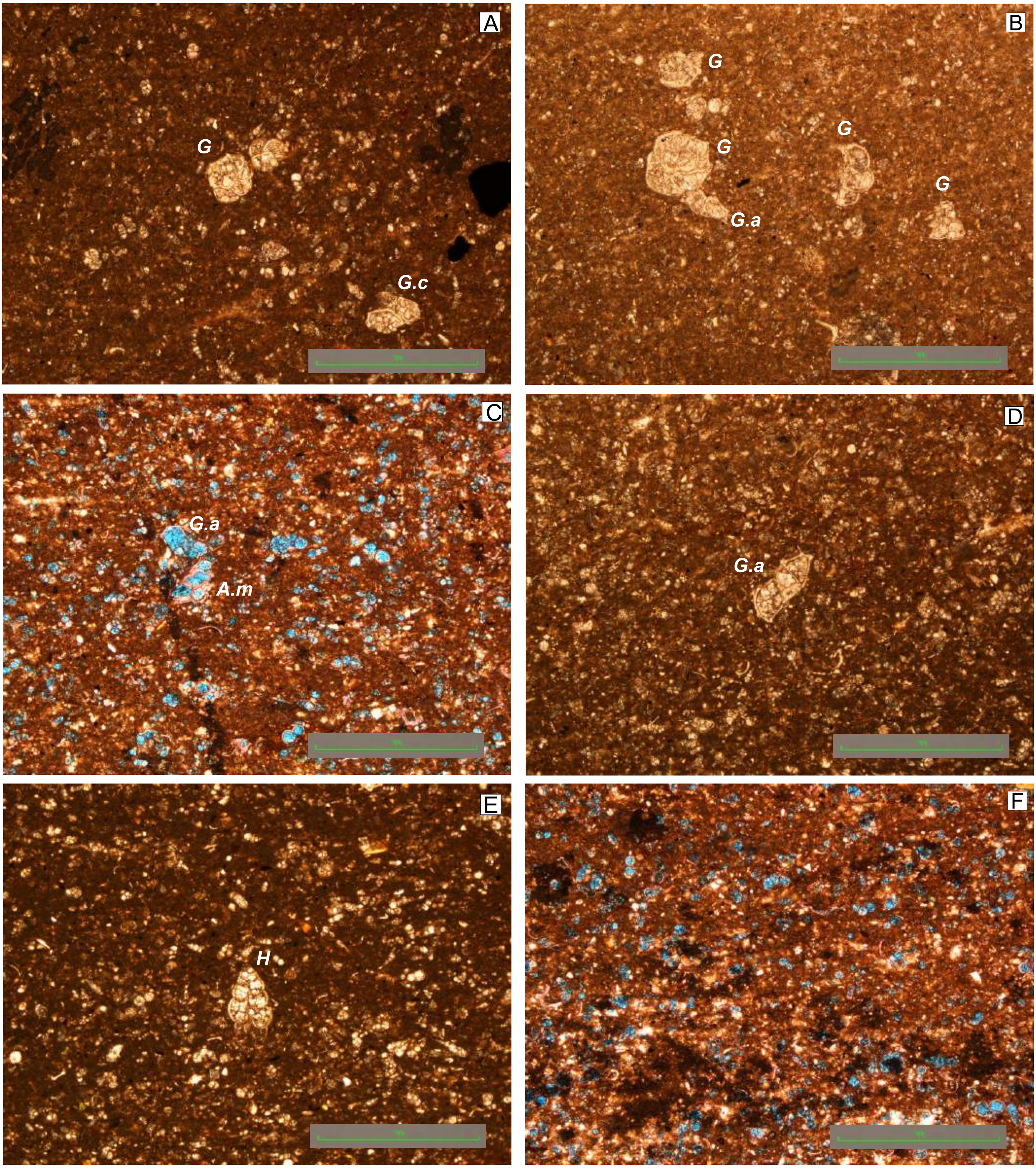
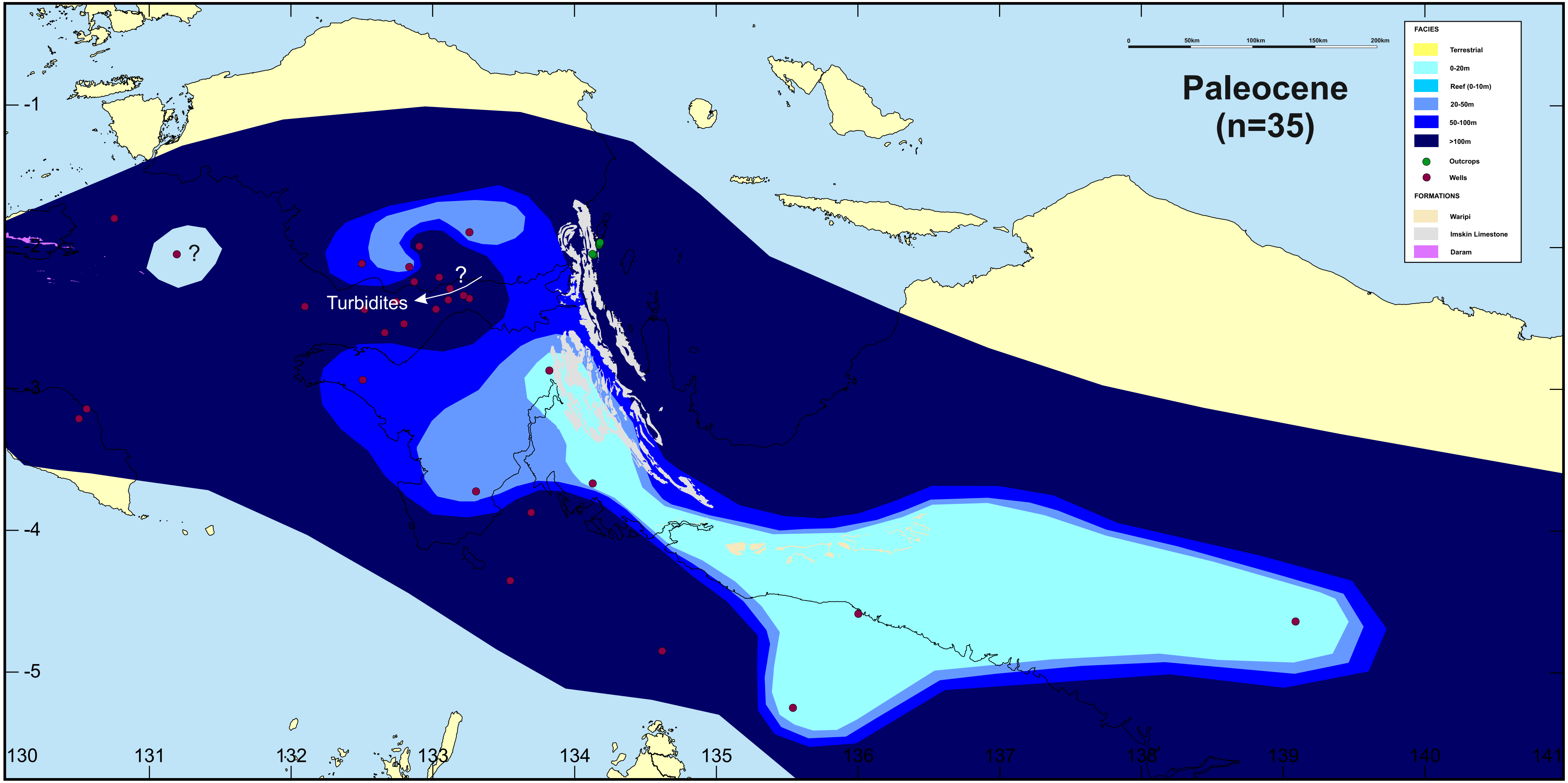
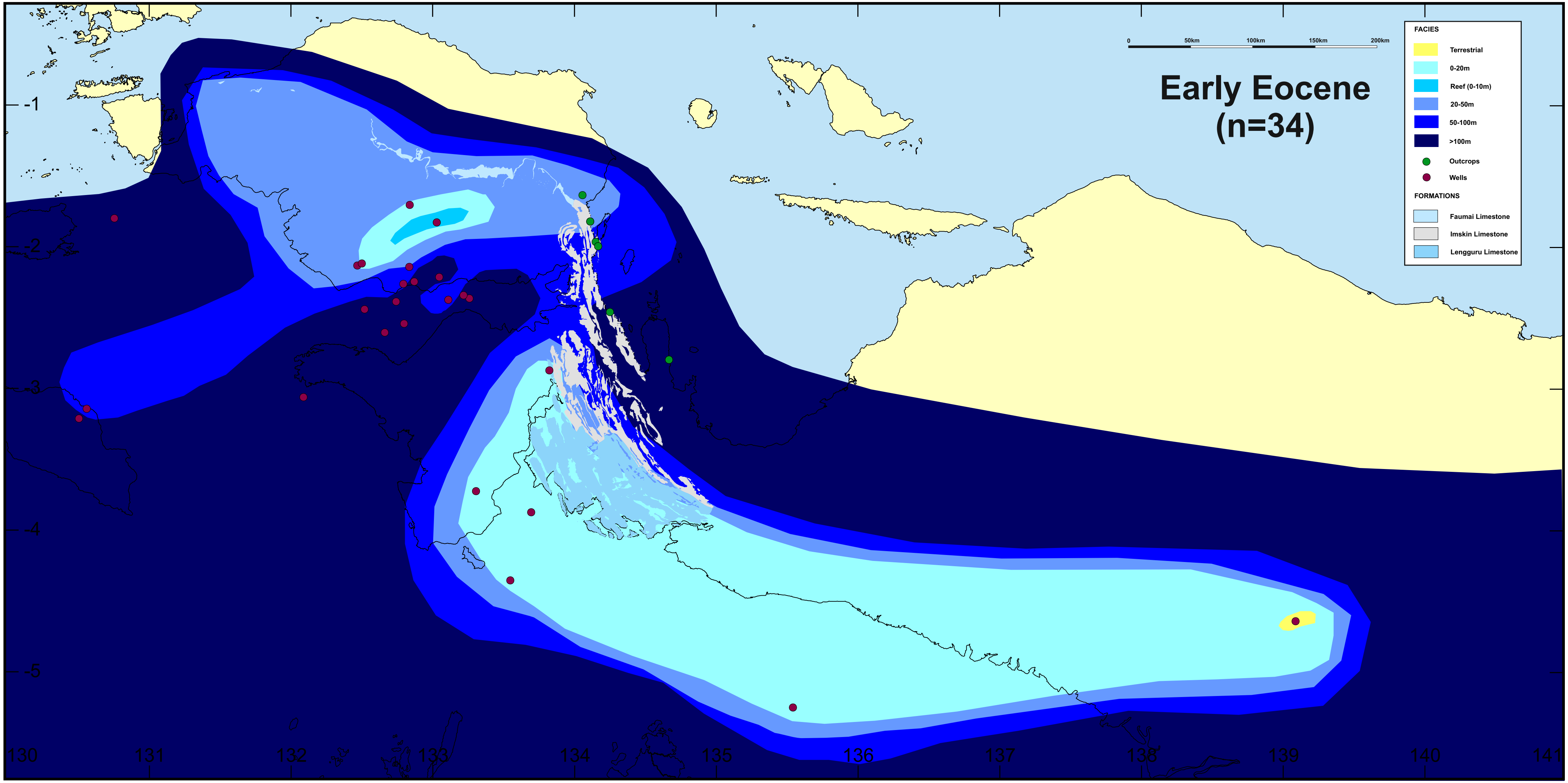


Figure 16



Paleocene
(n=35)
FACIES
Terrestrial
0-20m
Reef (0-10m)
20-50m
50-100m
>100m
Outcrops
Wells
FORMATIONS
Waripi
Imskin Limestone
Daram
0
50km
100km
150km
200km
Turbidites
?
?
-1
-2
-3
-4
-5
130
131
132
133
134
135
136
137
138
139
140
141

Figure 17



Early Eocene
(n=34)
0
50km
100km
150km
200km
FACIES
Terrestrial
0-20m
Reef (0-10m)
20-50m
50-100m
>100m
Outcrops
Wells
FORMATIONS
Faumai Limestone
Imskin Limestone
Lengguru Limestone
-1
-2
-3
-4
-5
130
131
132
133
134
135
136
137
138
139
140
141

Figure 18

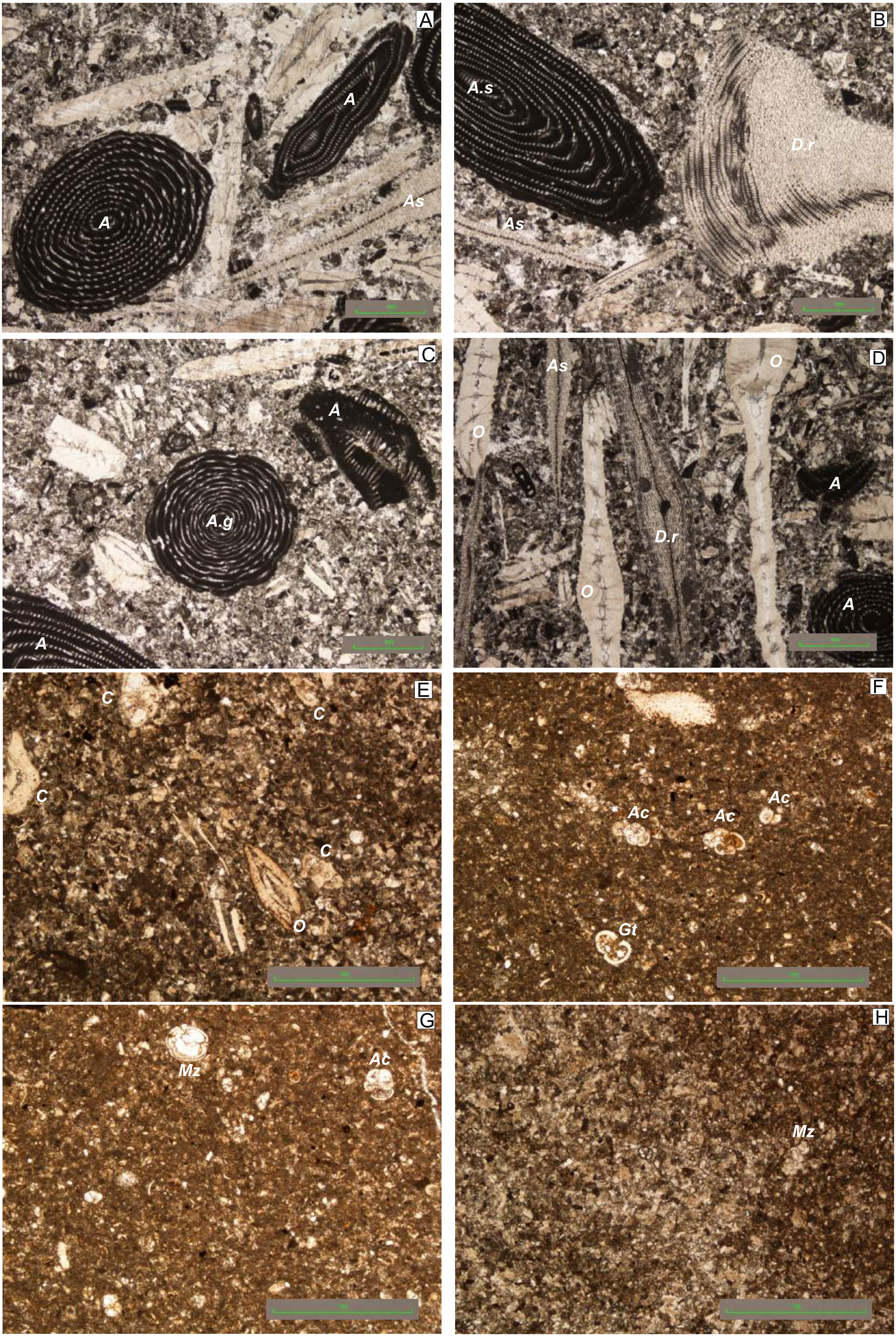

A
A
A
As
B
A.s
D.r
As
C
A
A.g
A
D
As
O
O
A
D.r
O
A
E
C
C
C
C
O
F
Ac
Ac
Ac
Gt
G
Mz
Ac
H
Mz

Figure 19

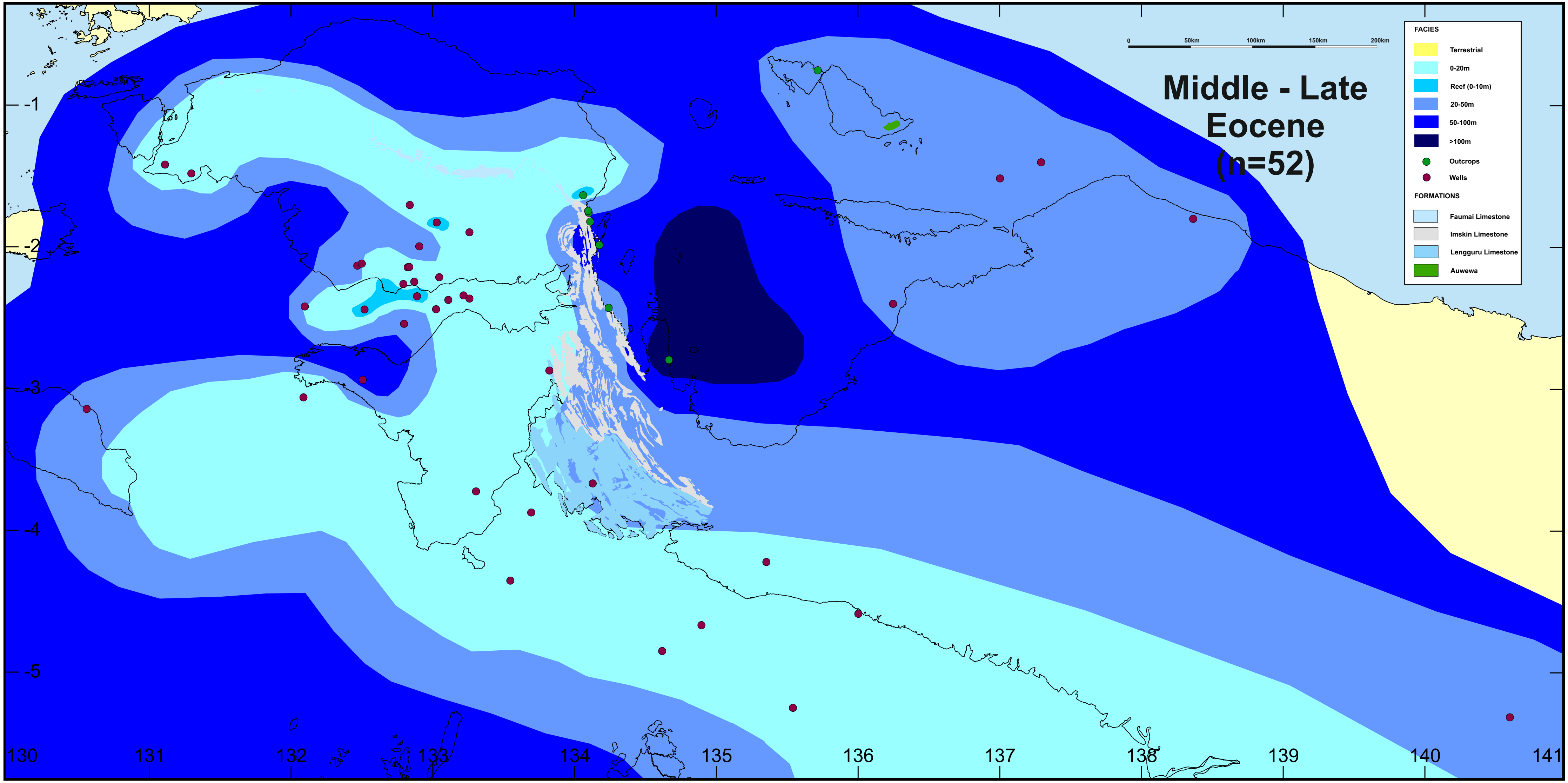

Middle - Late Eocene (n=52)
0
50km
100km
150km
200km
FACIES
Terrestrial
0-20m
Reef (0-10m)
20-50m
50-100m
>100m
Outcrops
Wells
FORMATIONS
Faumai Limestone
Imskin Limestone
Lengguru Limestone
Auwewa
-1
-2
-3
-4
-5
130
131
132
133
134
135
136
137
138
139
140
141

Figure 20

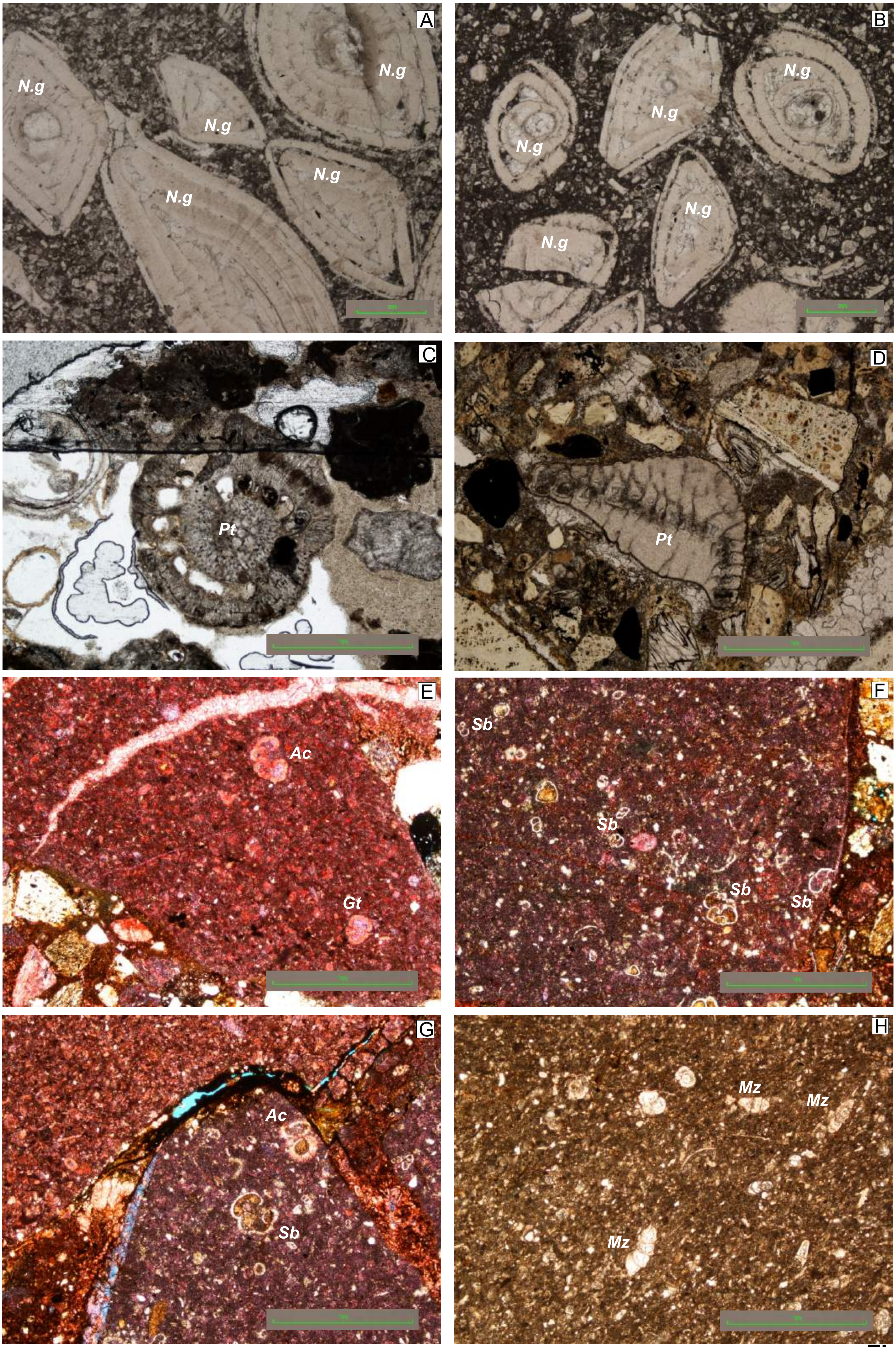

A
N.g
N.g
N.g
N.g
N.g
B
N.g
N.g
N.g
N.g
N.g
C
Pt
D
Pt
E
Ac
Gt
F
Sb
Sb
Sb
Sb
G
Ac
Sb
H
Mz
Mz
Mz

Figure 21

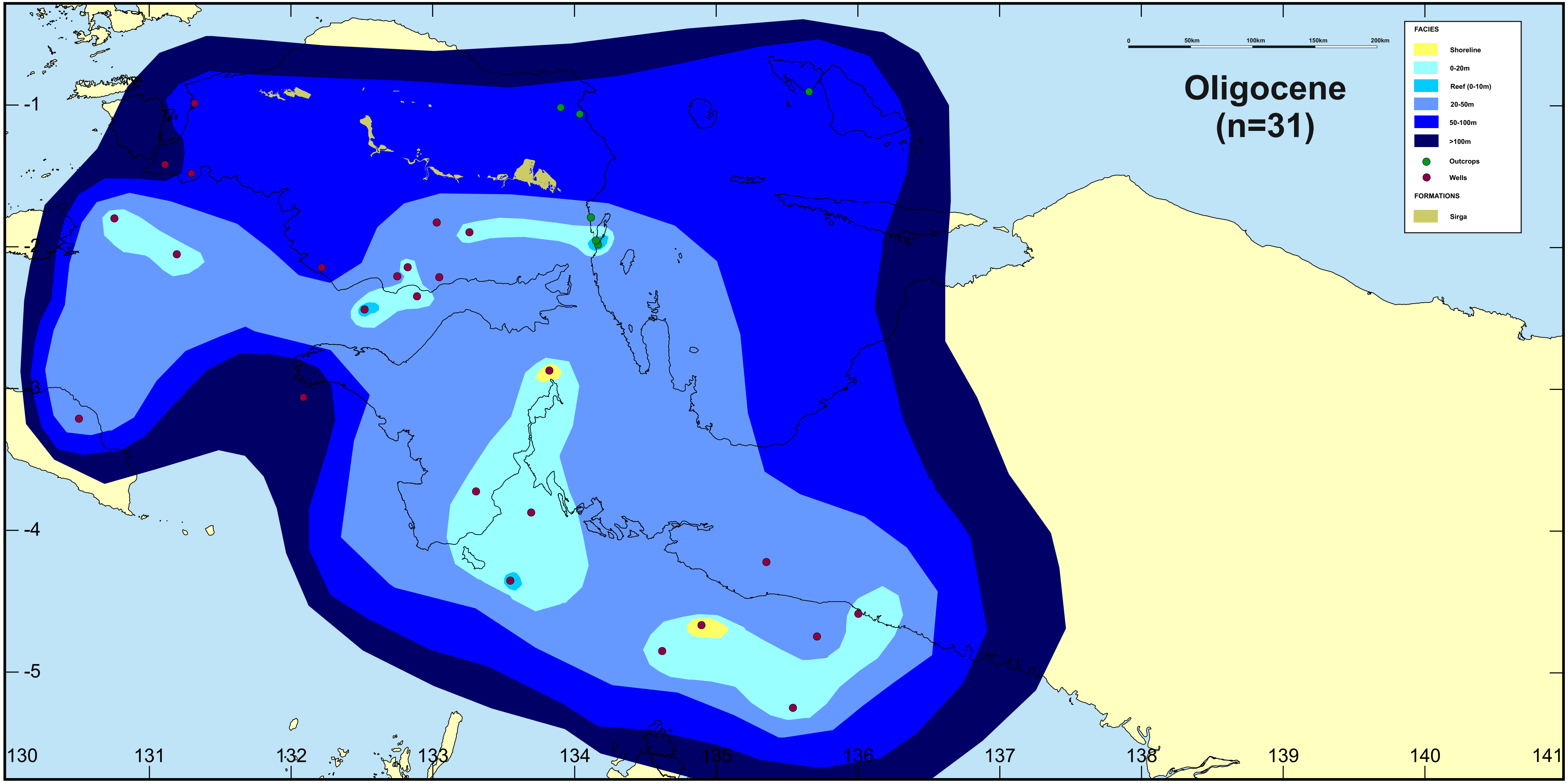

Oligocene
(n=31)
FACIES
Shoreline
0-20m
Reef (0-10m)
20-50m
50-100m
>100m
Outcrops
Wells
FORMATIONS
Sirga
0
50km
100km
150km
200km
-1
-2
-3
-4
-5
130
131
132
133
134
135
136
137
138
139
140
141

Figure 22

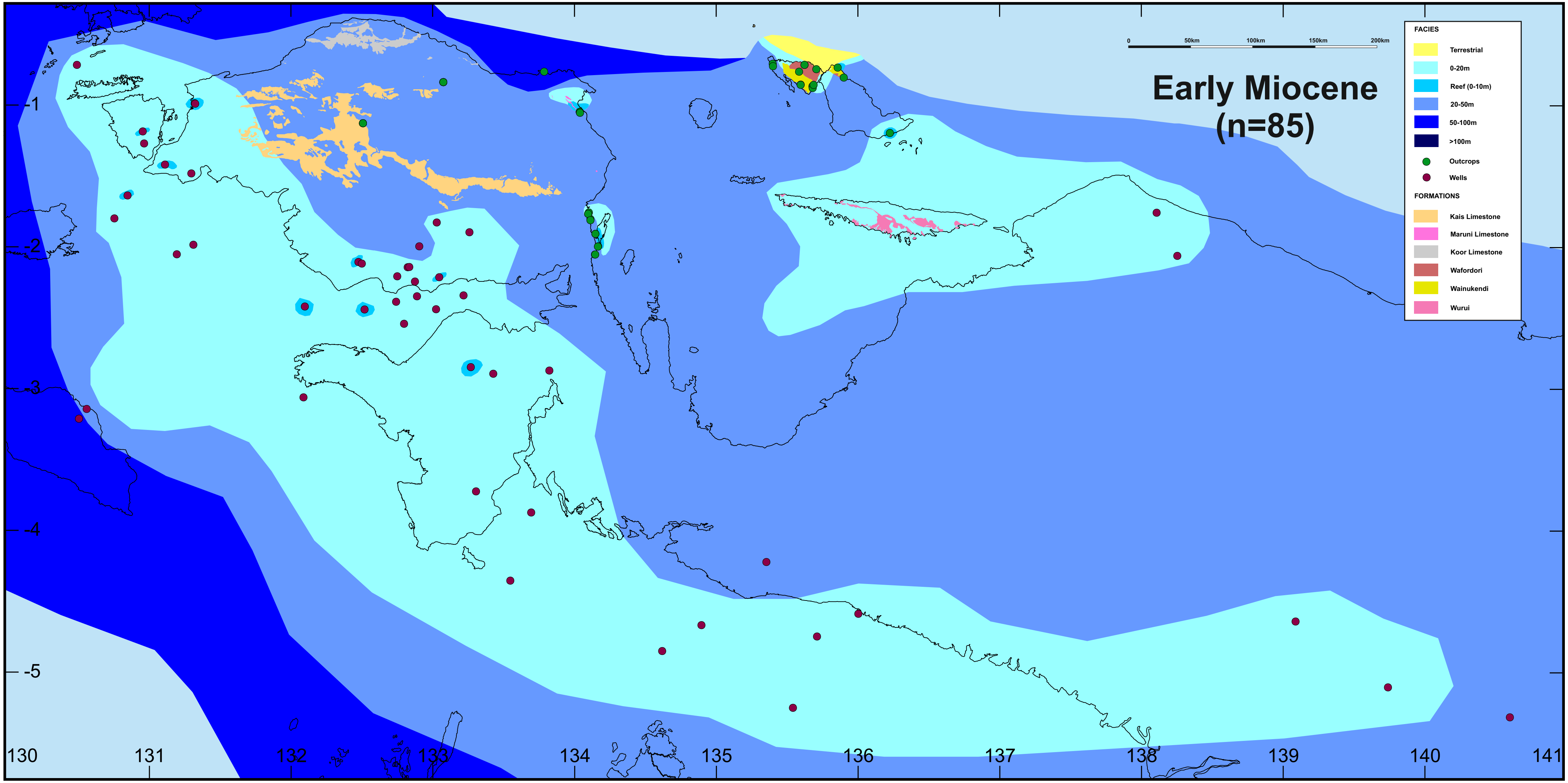

Early Miocene
(n=85)
0
50km
100km
150km
200km
FACIES
Terrestrial
0-20m
Reef (0-10m)
20-50m
50-100m
>100m
Outcrops
Wells
FORMATIONS
Kais Limestone
Maruni Limestone
Koor Limestone
Wafordori
Wainukendi
Wurui
-1
-2
-3
-4
-5
130
131
132
133
134
135
136
137
138
139
140
141

Figure 23

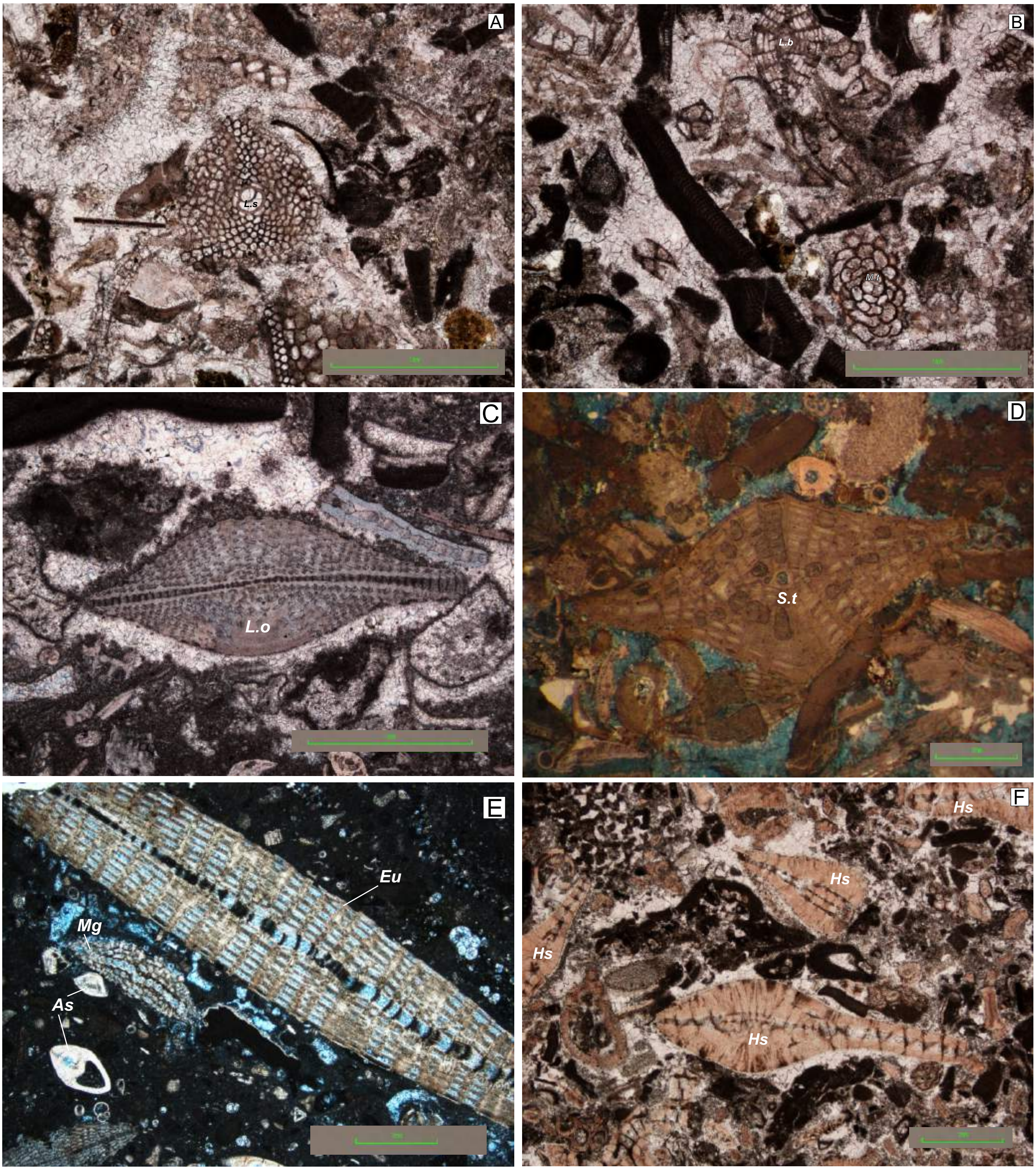


Figure 24

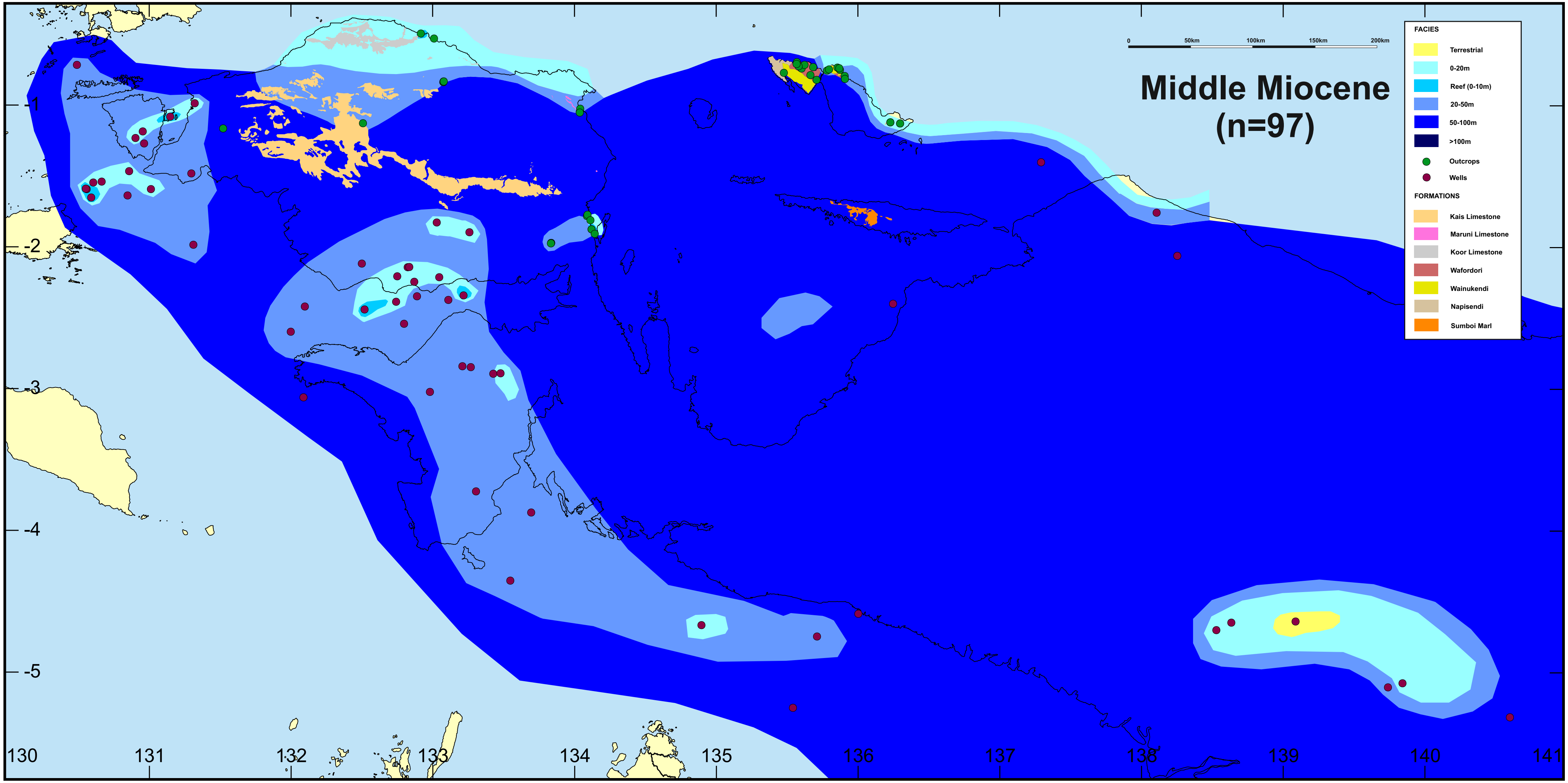

0
50km
100km
150km
200km
Middle Miocene
(n=97)
FACIES
Terrestrial
0-20m
Reef (0-10m)
20-50m
50-100m
>100m
Outcrops
Wells
FORMATIONS
Kais Limestone
Maruni Limestone
Koor Limestone
Wafordori
Wainukendi
Napisendi
Sumboi Marl
-1
-2
-3
-4
-5
130
131
132
133
134
135
136
137
138
139
140
141

Figure 25

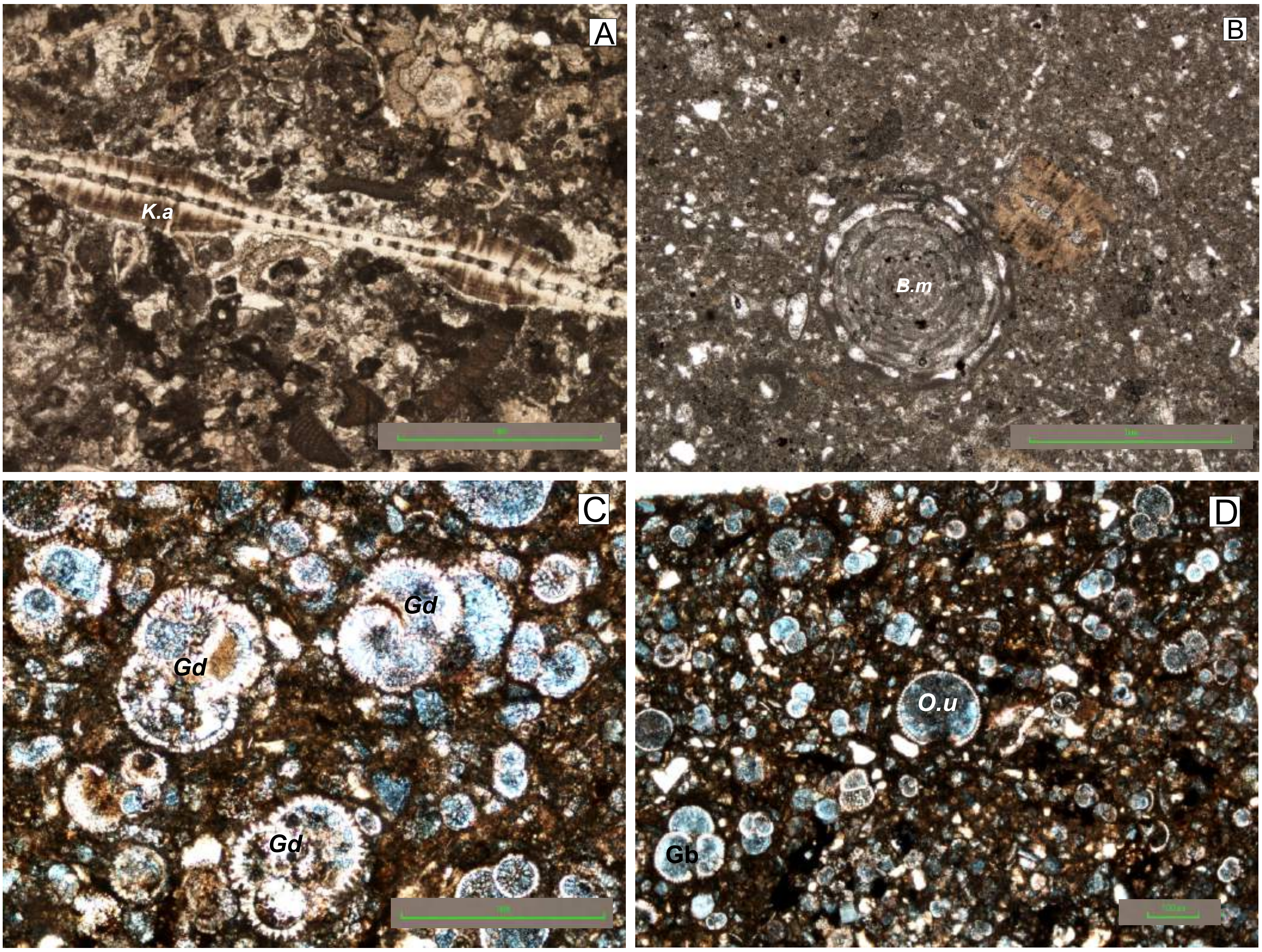


Figure 26

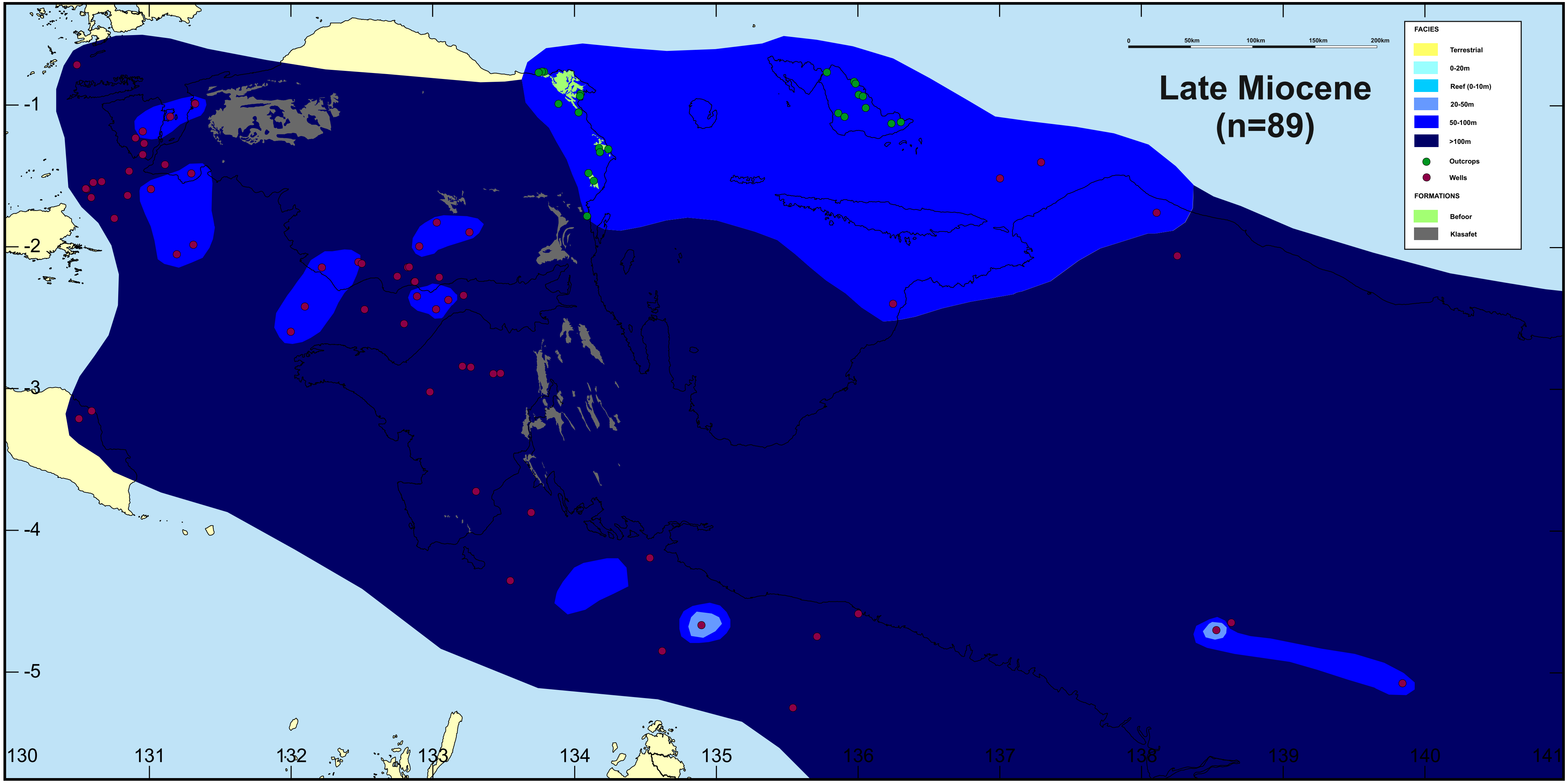
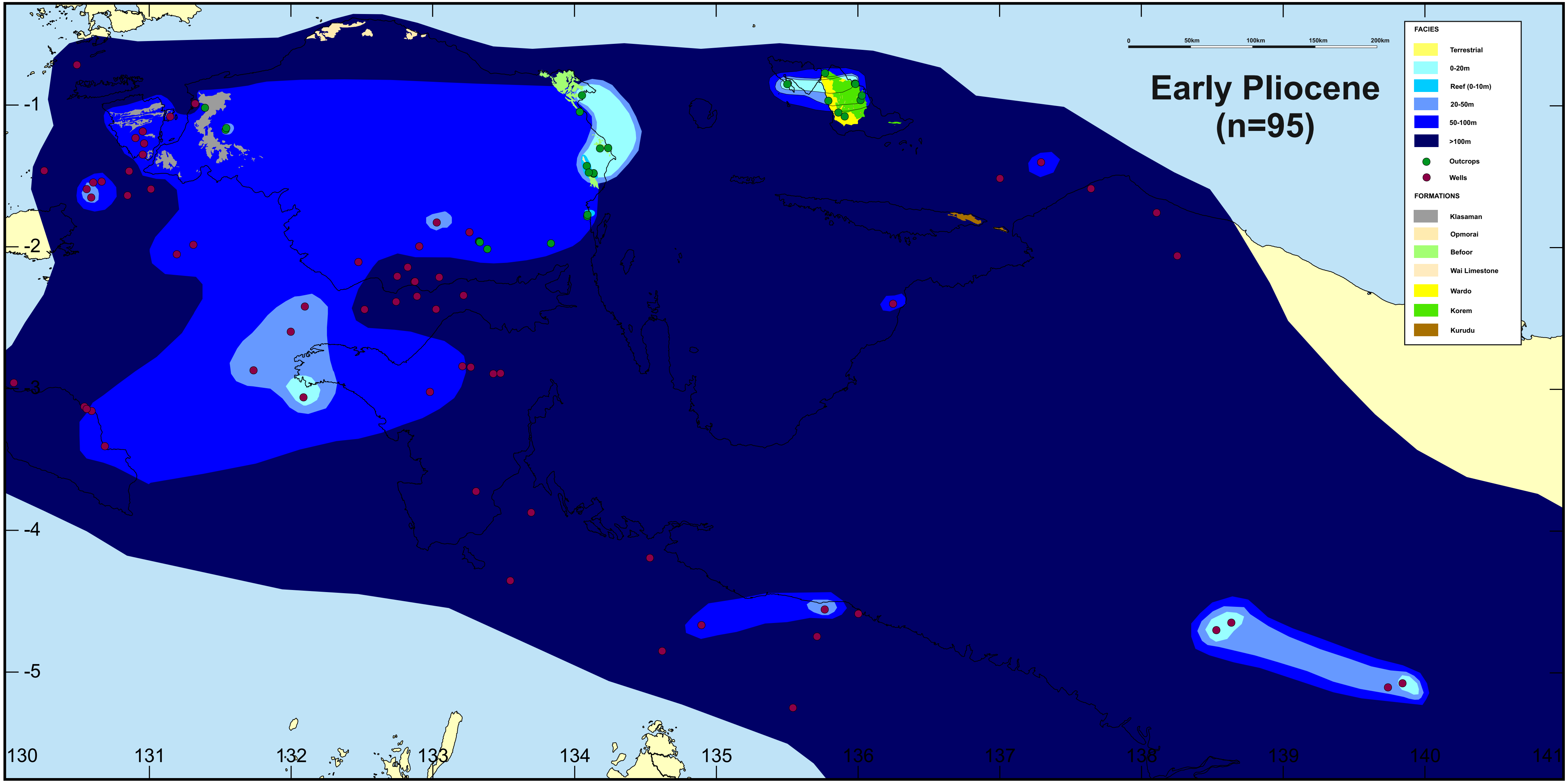

Late Miocene
(n=89)
0
50km
100km
150km
200km
FACIES
Terrestrial
0-20m
Reef (0-10m)
20-50m
50-100m
>100m
Outcrops
Wells
FORMATIONS
Befoor
Klasafet
130
131
132
133
134
135
136
137
138
139
140
141
-1
-2
-3
-4
-5

Figure 27



Early Pliocene
(n=95)
0
50km
100km
150km
200km
FACIES
Terrestrial
0-20m
Reef (0-10m)
20-50m
50-100m
>100m
Outcrops
Wells
FORMATIONS
Klasaman
Opmorai
Befoor
Wai Limestone
Wardo
Korem
Kurudu
-1
-2
-3
-4
-5
130
131
132
133
134
135
136
137
138
139
140
141

Figure 28

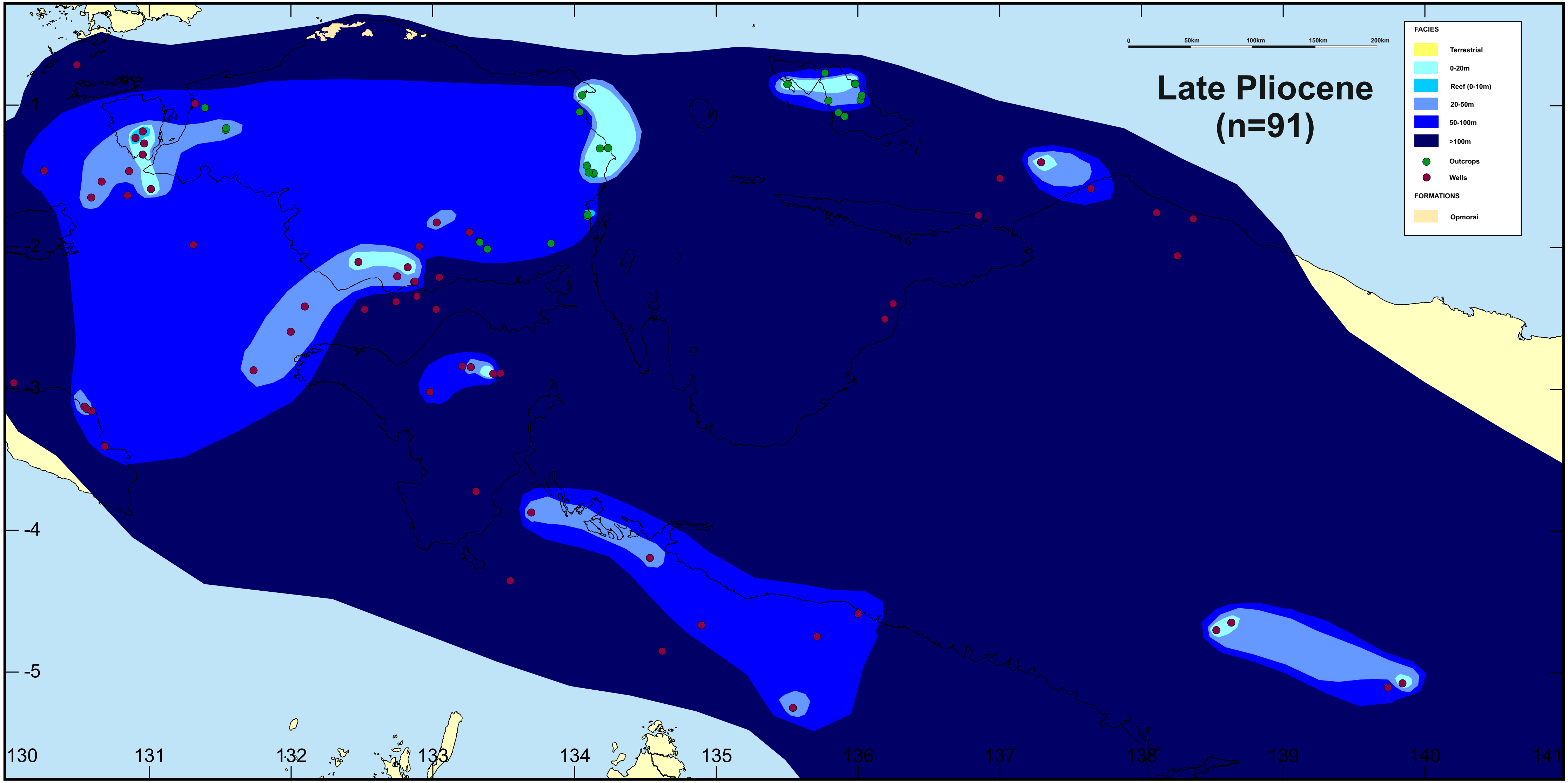
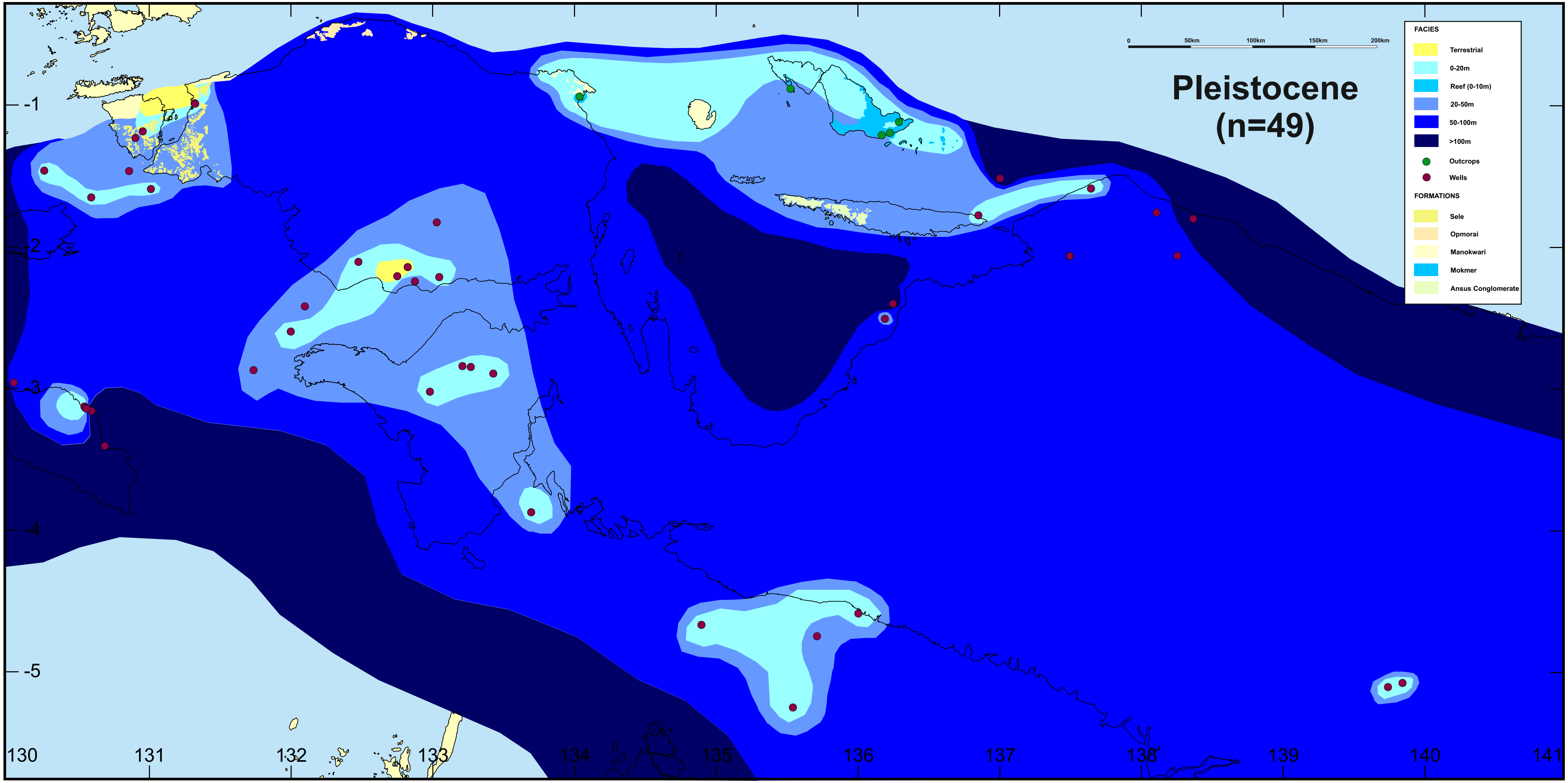

Late Pliocene
(n=91)
FACIES
Terrestrial
0-20m
Reef (0-10m)
20-50m
50-100m
>100m
Outcrops
Wells
FORMATIONS
Opmorai
0
50km
100km
150km
200km
130
131
132
133
134
135
136
137
138
139
140
141
-1
-2
-3
-4
-5

Figure 29



Pleistocene
(n=49)
0
50km
100km
150km
200km
FACIES
Terrestrial
0-20m
Reef (0-10m)
20-50m
50-100m
>100m
Outcrops
Wells
FORMATIONS
Sele
Opmorai
Manokwari
Mokmer
Ansus Conglomerate
-1
-2
-3
-4
-5
130
131
132
133
134
135
136
137
138
139
140
141

Figure 30