Relative relative sea-level change in western New Guinea recorded by regional biostratigraphic data

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Abstract

We present new biostratigraphic analyses of approximately 200 outcrop samples across western New Guinea. These data were used to reconstruct palaeogeography of the region from the Silurian to present day. Biostratigraphic ages and palaeodepositional environments were interpreted from occurrences of planktonic and larger benthic foraminifera, together with other fossils and environmental indicators where possible. These data were compared with existing geological maps and regional hydrocarbon well data to develop a more regional understanding of how palaeoenvironments and palaeogeographies changed through time in western New Guinea. Our analysis of these data identified two major transgressive-regressive cycles in regional relative sea-level with peak heights occurring 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. Relative sea-levels increased during a regional transgressive event that occurred between the Late Jurassic and the Late Cretaceous. This is particularly marked by widespread carinate planktonic foraminifera found in sediments of this age in various outcrops and wells across the region. Sea-levels dropped during a regressive event between the Late Cretaceous and the Paleogene, resulting in the widespread development of shallow water carbonate platforms by the Middle to Late Eocene. A minor transgressive event occurred during the Oligocene, but this ceased in the Early Miocene, due to the collision of the Australian continent with intra-Pacific island arcs. This collision event resulted in widespread uplift, which is marked by a regional unconformity. Carbonate deposition continued in platforms that developed in the shallow seas until these were drowned during another transgressive event in the

Middle Miocene. This transgression reached its peak in the Late Miocene and was followed by a further regression culminating in the present day topographic expression of western New Guinea.

Keywords: Tectonics; planktonic; larger benthic; foraminifera; paleogeography; biogeography

1. Introduction

New Guinea has represented the northernmost boundary of the Australian Plate from the present until at least the Permian (perhaps as early as the Carboniferous), when New Guinea was part of an Andean-style arc system that extended around a large portion of Gondwana (Charlton, 2001; Hall 2002; 2012; Hill and Hall 2003; Crowhurst et al., 2004; Metcalfe 1998; 2009; Gunawan et al., 2012; 2014; Webb and White, 2016; Jost et al., submitted around xmas). This long-lived plate boundary records evidence of numerous tectono-thermal events during the Paleozoic, Mesozoic and Cenozoic (e.g. Visser and Hermes, 1962; Pieters et al., 1983; Davies and Jaques 1984; Pigram and Davies 1987; Pigram and Symonds 1991; Baldwin and Ireland 1995; Baldwin et al., 2004; 2012; Davies 2012; Bailly et al., 2009; Holm et al., 2013; 2015; 2016). However, much of the geology of New Guinea is also dominated by siliciclastic and carbonate deposition during seemingly long periods of quiescence (Pieters et al., 1983; Pigram; Visser and Hermes, 1962; Fraser et al., 1993; Hill, 1991; Davies, 2012; Baldwin et al., 2012). We focus on the age and depositional environment of these sediments in western New Guinea, an area that is relatively underexplored, with the last major geological mapping campaign being conducted in the 1980's (e.g. Masria et al., 1981; Pieters et al., 1983; Dow et al., 1986; Atmawinata et al., 1989; Pieters et al., 1989; Dow et al., 1990; Harahap et al., 1990; Pieters et al., 1990; Robinson et al., 1990; Panggabean et al., 1995). We present new biostratigraphic age data based on benthic and planktonic foraminifera, as well as facies analyses from nearly 200 outcrop samples from western New Guinea. Where possible, we compared these results with publicly available hydrocarbon well locations, biostratigraphic analyses and interpreted depositional environments (e.g. Visser and Hermes, 1962; Fraser et al., 1993). The aim of this work was to better establish the duration and facies distribution of strata to better understand the spatio-temporal distribution of periods of queisence at the northern margin of the Australian Plate between the Silurian and present day.

1.1 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. The results of this work are compiled and summarised in Visser and Hermes (1962). The observations that are reported in this work lay the foundation for the stratigraphy of Irian Jaya and remain highly relevant, despite this work being completed before the advent of plate tectonics. The stratigraphy and tectonic development of western New Guinea was refined by Indonesian and Australian government geologists between 1978 and 1982; the results of which are summarised in Pieters et al. (1983).

1.2 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 and Neck, and part of the Body are within the Indonesian provinces of West Papua and Papua (formerly known as Irian Jaya). The rest of the Bird’s Body and the Tail are found in 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 (e.g. Bailly et al., 2009; Francois et al., in press - Lithos)(Fig.1). 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). Rocks to the south of New Guinea are primarily of Australian continental affinity whereas those to the north consist of ophiolite and island arc volcanics of Pacific Plate provenance. These two domains are separated by a central, complex region of juxtaposed fault slices of sediments together with variably metamorphosed and granitic rocks, marking the suture (Fig. 1) formed during arc-continent collision in the Early Miocene, (e.g. 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, which accreted to Australian continental material to the south and west. The post-collisional stratigraphy of both domains is reasonably contiguous (Fig. 2).

We report data from strata that were deposited on the northern margin of the Australian continent from the Silurian to present, together with strata from the accreted intra-Pacific island arc(s), focussing primarily on the stratigraphic and palaeogeographic evolution of the Bird’s Head and Neck, together with the western part of the Body.

2. Depositional History of western New Guinea sediments

2.1 Australian Plate stratigraphy

The distribution of outcropping strata mapped by Masria et al., (1981); Pieters et al. (1983); Dow et al. (1986); Atmawinata et al. (1989); Pieters et al. (1989); Dow et al. (1990); Harahap et al. (1990); Pieters et al. (1990); Robinson et al. (1990); Panggabean et al. (1995) used in this study are depicted in Figure 3. The oldest strata within the Bird's Head consist of variably metamorphosed siliciclastic rocks considered to be derived from rocks to the south (i.e. Australian craton). These have poor age control, but were assigned a Silurian-Devonian age from several graptolites and because these rocks are cross-cut by Carboniferous and Permian intrusions (Visser and Hermes, 1962; Pieters et al., 1983). These sequences are known as the Kemum and Aisasjur Formations (Fig. 3) and are considered to represent distal and proximal turbidite deposits, respectively (Visser and Hermes, 1962; Pieters et al., 1983). There are no other rocks of this age exposed in western New Guinea, however, these may be equivalent to the XXX found in Papua New Guinea, and are potentially equivalent to the widespread deposition of Ordovician turbidite sequences across much of eastern Australia (e.g. Fergusson?; Peacock?).

The oldest carbonate unit in western New Guinea is the Modio Dolomite of the Central Ranges (Fig. 3), deposited during the Silurian-Devonian (Fig. 2; Pieters et al., 1983). During the Carboniferous, a phase of volcanism is recorded by K-Ar data (Jost et al., XXXX – IPA 2017?), this was followed by approximately 100 My of volcanic quiescence before further volcanism during the Triassic. The Carboniferous to Permian was a period of relatively stable paralic sediment deposition, with occasional shallow marine incursions marked by thin limestone beds in New

Guinea’s Central Range. The Permo-Carboniferous Aifam Group (Fig. 3) contains various terrestrial and marine deposits (Visser and Hermes 1962, Chevallier & Bordenave 1986, Dow et al., 1988). In this group the Aimau, Ainim and Aiduna formations are reported to contain conglomerates, red beds and coal seams suggesting a terrestrially influenced, possibly deltaic and lacustrine, depositional setting (Norvick et al., 2003), the Aifat mudstone however may have been deposited in a basinal setting (Pieters et al., 1983).

During the Triassic a second phase of volcanism is recorded by the presence of granitoids in the Netoni Intrusive Complex (Webb and White, 2016), Anggi Granite, Wariki Granodiorite, Warjori Granite, Central Range (Crowhurst, XXXX) and detrital zircons within the Tipuma Formation derived from ash fall tuff (Gunawan et al., 2012; 2014). The only sedimentary rocks known from the Bird’s Head are arid terrestrial deposits of the Tipuma Formation (Fig. 3), some of which interpreted to have been deposited as fluvial run off from a volcanic arc (Gunawan et al., 2012; 2014) 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. In the Bird’s Head, deposition of siliciclastic material forming the Tamrau Formation and Kembelangan Group (Fig. 3) correlated to the shelfal deposits of the Demu and Lelintu Formations of Misool (Hasibuan, 1990), persisted throughout the Jurassic and into the Late Cretaceous (Fig. 2). On Misool

The Cretaceous siliciclastic units of the Kembelangan Group include the Jass Formation, Piniya Mudstone and the Woniwogi and Ekmai Sandstones (Fig. 3). 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, which 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; Fig. 3). 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). In deep-water areas to the north of this basin, turbidites of the Daram Formation (Norvick et al., 2003) were deposited. Brash et al. (1991) suggest that in these deep-water areas 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 (Figs. 2 and 3).

2.1 Pacific Plate and contiguous stratigraphy

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 a phase of collision in the Early Miocene (Wilson, 2002). Following collision, 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 (Figs. 2 and 3), 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 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. These include a mixture of spot samples as well as samples from logged stratigraphic sections. All samples were thin sectioned and examined for 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 20 time intervals to show the palaeogeographic 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. These preferences are summarised in Figure 4. Our palaeogeographic maps are subdivided into five relative bathymetries according to the bathymetric preferences (Fig. 4) assigned to samples with depth-diagnostic foraminiferal assemblages. 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, we present our reinterpretations of biostratigraphic, wireline log, stratigraphic columns, palaeogeographies and palaeoenvironmental interpretations from public domain data from 150 exploration wells (Fig. 5) and regional stratigraphy of individual reef complexes within the Salawati and Bintuni basins (Table 1). 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.

Palaeogeographic maps were constructed from the new analyses of outcrop and well data and synthesis of regional facies distributions collated from the public domain. The depositional bathymetries of samples and well intervals interpreted for each time slice were plotted using ArcGIS so that the spatial distribution of facies could be compared with existing palaeogeographic maps of the region (Visser and Hermes, 1962; Audley-Charles, 1965; 1966; Vincelette, 1973; Redmond and Koesoemadinata, 1976; Collins and Qureshi, 1977; Gibson-Robinson and Soedirdja, 1986; Brash et al., 1991; Norvick et al., 2003; Golonka, 2006; 2009). The new palaeogeographic maps were overlain on the present day configuration of western New Guinea (e.g. Visser and Hermes, 1962; Audley-Charles, 1965; 1966; Gibson-Robinson and Soedirdja, 1986; Brash et al., 1991) as the position of New Guinea relative to Australia has not changed much since Permian (Audley-Charles, 1965; 1966; Gunawan et al., 2012; 2014). Consequently we do not attempt the palinspastic restoration of structural features, such as the displacement of faults or large-scale rotation of crustal fragments (e.g. Norvick et al., 2003; Golonka et al., 2006; 2009, Charlton, 2010; Hall, 2012). 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 and as an independent means to assess periodicity of localised tectonic driven uplift/subsidence events compared to global changes in sea level.

A regional relative sea-level curve for Western New Guinea throughout the Phanerozoic was produced by calculating the average bathymetry of all points analysed within a specific time periods. For a given time period the range, maximum, minimum and average bathymetry was calculated so that an a modal relative sea-level curve for Western New Guinea could be calculated. Error bars were included to highlight the range of bathymetries within the time period. This regional relative sea-level curve could then be compared to global sea-level curves (e.g. Haq and Al-Qahtani, 2005; Müller et al., 2008; Snedden and Liu, 2010) to assess potential timing of tectonic events.

4. Results and discussion of palaeogeographic reconstructions

The following sections present both the results of the palaeogeographic reconstructions and discussion of how these maps compare to previously published work from similar studies.

4.1 Silurian

During the Silurian, bathymetries in excess of 100m are interpreted across much of the Bird's Head and Neck, shallowing towards the south-east (Fig. 6A). This interpretation is based on published descriptions and distribution of the widespread basement block comprising the Kemum Formation. Two wells reviewed by this study penetrated 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 including *Monograptus turriculatus* and *M*. *marri* (Visser and Hermes, 1962), typical of Silurian 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. 6A). The prevalence of deep water settings in western New Guinea during the Silurian supports Golonka et al.'s (2006) interpretation that large areas in the Gondwana were submerged at this time.

A broad south-easterly shallowing trend towards the Bird's Body is interpreted (Fig. 6A). This is 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, and presence of late Silurian limestones containing the tabulate coral *Halysites* spp. in the Central Ranges (Fig. 6A; Visser and Hermes, 1962). We interpret the Modio Dolomite to have a shallow-water carbonate-rich protolith, relative to the deeper water sediments to the north-west.

4.2 Devonian

The south-east directed shallowing trend continued into the Devonian where bathymetries in excess of 100m are interpreted in the Bird's Head and Neck (Fig. 6B). This interpretation is based on published descriptions and distribution of the Kemum and Aisasjur Formations in the north-west. Two wells reviewed by this study penetrated Devonian material, confirming the presence of shallow water facies to the south-east of the study area. The expansion of moderate water facies, between 20m and 50m depth, in the south-east compared to the Silurian is due to an increased number of data points. These additional data points incorporated reinterpretation of Devonian age outcrop samples collected in the Central Range, reported by Visser and Hermes (1962).

Visser and Hermes (1962) report Devonian age micaceous sandstones and impure limestones found within river pebbles in the Central Ranges. These rocks contain a fossil assemblage that contains gastropods, scaphopods, bivalves, brachiopods, including *Spirifer* spp., and tabulate corals including *Favosites* spp. and *Heliolites* spp. These assemblages and rock types are indicative of shallow marine photic zone and neritic depositional settings, reflected in our palaeobathymetric reconstruction (Fig. 6B). South-east directed shallowing may continue south into Australia, supporting the Golonka et al. (2006) model of shallow marine siliciclastics and carbonates across much of Papua New Guinea, with land in Australia.

4.3 Carboniferous

Palaeogeographic reconstructions of the Carboniferous are based on published descriptions of formations of this age and a review of 14 wells (Fig. 6C). No new analyses of outcrop samples were conducted by this study. Visser and Hermes (1962) interpret paralic sediments across much of western New Guinea during the Permo-Carboniferous (Fig. 6C) based on data from two wells, and six outcrop samples. However, we interpret that the influence of marginal marine environments occurred more towards the Permian. Based on the presence of conglomerates, red beds and coal seams observed within the Carboniferous age Aimau, Ainim and Aiduna Formations of the Bird's Head and Neck observed within many of the 14 study wells, a widespread terrestrial depositional setting is interpreted for the Carboniferous (Fig. 6C; Pieters et al., 1983; Fraser et al., 1993; Norvick et al., 2003). This is in contrast to the interpretation of Golonka et al. (2006) where a deep water slope setting is inferred along the norther margin of New Guinea.

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. Consequently, a widespread terrestrial palaeodepositional setting is interpreted across the region. This is further supported by the presence of plant-bearing terrestrial sediments reported from the Central Ranges (REF).

4.4 Permian

The Permian palaeogeography interpreted by this study is based entirely on published lithological descriptions and a review of 50 wells (Fig. 6D). 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. Our interpretation broadly agrees with Visser and Hermes' (1962) interpretation of the distribution of marginal marine sediments extending through the central Bird's Head, Neck and Body (Fig. 6D). We extend the landmass of Audley-Charles (1965) farther north, based on terrestrially influenced deposits recorded from wells in this region.

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. 6D). This terrestrial zone contains the land plants *Glossopteris* and *Gangamopteris* plants, reported to stretch from the Irian Jaya to Papua New Guinea (Fontaine, 2001). The Permian landmass of New Guinea was surrounded by shallow water units, interpreted to have been deposited in water depths no greater than 20m (Fig. 6D), based on the presence of shallow water limestones that contain fusuline-algal assemblages similar to that of Ratburi Limestone in peninsular Thailand (Dawson, 1993; Fontaine, 2001)

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 6D 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 within 11 wells (Fig. 6E). Evidence from outcrop and well data push the Australian-New Guinea landmass and paralic sediments of Audley-Charles (1966) farther north so that much of western New Guinea is emergent during the Triassic, contrasting to the interpretation that northern New Guinea was within a deep waer setting at this time (Audley-Charles, 1966). Our interpretations refine the palaeogeographic maps of Visser and Hermes (1962) and Norvick et al. (2003) who suggest the presence of a landmass extending from the central Bird's Head, Neck and southern margin of the Bird's Body (Fig. 6E).

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) and fluvial deposits

(Gunawan et al., 2012; 2014). This is supported by the presence of oxidised sediments and continentally derived palynomorphs reported within many of the wells interpreted to contain terrestrial deposits (Fig. 6E) indicating that continental deposits are widespread across much of western New Guinea and Seram during the Triassic (Fig. 6E). Other wells contain paralic and/or supralittoral sediments interpreted here to represent shallow water depths, deposited in less than 20m water depth, together with Norian age reefal deposits reported from the island of Misool (Fig. 6E; Van Bemmelen, 1949; Visser and Hermes, 1962; Audley-Charles, 1966). A restricted marine environment is interpreted by Visser and Hermes (1962) to the far east of the study area, here we interpret the presence of a reef north of the data points here which provides the barrier by which the back-reef environment is restricted (Fig. 6E).

4.6 Early Jurassic

Early Jurassic sediments are reported from seven wells located in the on- and offshore Bird's Head and Body (Fig. 6F). These wells intersected 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 terrestrial deposits is interpreted to extend from the Bird's Head, into the Neck and Body (Fig. 6F), and possibly farther into Australia as well as farther east along the Sula Spur. A barrier reef is interpreted to cause restriction in the marine environment to the east of the study area as a continuation of Visser and Hermes (1962) interpretation of the Late Triassic. By the Early Jurassic wholly open marine strata are reported from the island of Misool (Visser and Hermes, 1962) and deep water clays and marls are reported along the northern margin of a landmass extending from the Bird's Head and Neck, and centre of the

Body (Audley-Charles, 1966; Norvick et al., 2003). Therefore, water depths between 50m and 100m are interpreted to surround the central New Guinea landmass (Fig. 6F).

4.7 Middle Jurassic

Across western New Guinea, a period of Late Triassic to Early Jurassic terrestrial deposition, lasting at least 28 Ma, was succeeded by deeper water sedimentation during a transgressive event in the Middle Jurassic (Audley-Charles, 1966; Pieters et al., 1990; Lunt and Djaafar, 1991; Gunawan et al., 2012; Fig. 6G). This is supported by review of 37 wells containing Middle Jurassic strata and material from eight outcrop locations.

Our reconstructions support Norvick et al.'s (2003) Middle Jurassic interpretation of two separate small landmasses around Bird's Head and Neck, respectively, separated by shelfal clastic deposits between. Deep water settings are interpreted along the northern New Guinea margin, also supporting Norvick et al.'s (2003) interpretation of neritic clays found along this coast.

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. 6G). Two such landmasses were separated by a narrow seaway with water depths between 50m and 100m (Fig. 6G). 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 (Fig. 6G) due to the presence of fluvio-deltaic sediments reported within the CS-1X well and delta plain coals and organic claystones of the Inanwantan sequence (Fraser et al., 1993). 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. 6G).

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. 7). 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). Belemnites are also known from Papua New Guinea, Irian Jaya, Sula Islands and Misool further indicating widespread open marine deposition during the Middle Jurassic (Challinor, 1990).

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 may have been translated to its current position along the Sorong Fault Zone (Fig. 1) since the Pliocene, although the amount of displacement along this fault is uncertain.

4.8 Late Jurassic

Palaeogeographic reconstructions of this time interval are based on review of 35 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 saw the seaway between the two landmasses of the former Sula Spur attain water depths in excess of 100m (Fig. 6H). 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. 6H).

Audley-Charles (1966) plot a landmass over much of western New Guinea, with bathyal settings occurring along its northern margin. We interpret this boundary to be found along the central spine of New Guinea. Our interpretations again support Norvick et al.'s (2003) Late Jurassic interpretation of two separate small landmasses around Bird's Head and Neck, separated by shelfal clastic deposits. Deep water settings encroach around the margins of New Guinea throughout the Jurassic due to transgression.

The Woniwogi, Demu and Lelinta Formations are interpreted to be deep-water marine deposits, similar to the Kopai and Tamrau (Pieters et al., 1983; Hasibuan, 1990), based on the presence of glauconitic and argillaceous, fine-grained, distal sediments and bathyal agglutinated foraminifera such as *Glomospira* spp, and *Trochammina* spp. within some wells.

4.9 Early Cretaceous

Reconstructions of the Early Cretaceous are based on review of 23 wells, 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. 6I). Our reconstructions support those of Audley-Charles (1966) who interpret bathyal water depths depths west of the Bird's Head and in the northern half of the Bird's Body, with neritic facies to south and west of this boundary. This differs from Norvick et al. (2003) who place an isolated landmass within the central Bird's Head at this time.

Widespread deep water sedimentation 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. 6I). This is based on the presence of shelfal agglutinated and calcareous benthic foraminifera, such as *Lenticulina* spp., and sediments dominated by globular planktonic foraminifera including *Hedbergella* spp., *Heterohelix* spp. and *Ticinella* spp., and lack of carinate foraminifera, within wells along the southern New Guinea margin. 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 and Noordwest-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 where water depths in excess of 100m are interpreted across much of western New Guinea (Fig. 6J). This is evident from data reviewed from 65 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. 6J). This supports the interpretations of Visser and Hermes (1962) and Audley Charles (1966) who interpret widespread open marine and bathyal facies across the entire western New Guinea during the Late Cretaceous. The cause of a change in shallowing direction from the Early to Late Cretaceous is uncertain, although this may be a tectonic effect during a period of activity at this time.

Although our reconstructions agree with Norvick et al. (2003) that western New Guinea was submerged beneath deep water during the Late Cretaceous, Norvick et al. (2003) and Brash (1991) put the deposition of the Ekmai shallow water sandstones within the Bird's Neck. It is our interpretation that these have been displaced to their current position through thrust faulting. The Late Cretaceous shallow-water Ekmai sandstones, reported as late Campanian in age (Norvick et al., 2003), are interpreted to have been deposited farther to the north-east and translated to the Bird's Neck through shortening of approximately 200km to the southwest in the Lengguru Fold and Thrust Belt. This shortening accounts for the presence of the shallower water larger benthic foraminifera *Lepidorbitoides* and *Pseudorbitoides* in Late Cretaceous strata in the Bird's Neck region (Visser and Hermes, 1962). The '*in situ'* facies in the Bird's Neck are interpreted to be represented by the deep marine Piniya Mudstone, following the trend for increasing sea-level initiating in the Early Jurassic.

Many of the 65 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. 6J). 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 bulloides*, *Globotruncana linneiana*, *Globotruncanita conica*, *Globotruncanita*. *stuarti*, *Rugotruncana subcircumnodifer* and *Heterohelix globulus* (Fig. 8).

4.11 Paleocene

Following the Late Cretaceous relative sea-level high, water levels receded during the Paleocene leaving shallower water areas around the southern Bird's Head, Neck and Body (Fig. 6K). This is based on review of 53 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. 6K). This is based on the observation of the Waripi Formation 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 and offshore to the west, deeper waters in excess of 100m are encountered in many wells recording Daram Formation 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. We interpret that the Daram turbidites in central Bird's Head directed to the west (Fig. 6K). An exception to this trend are Daram sandstones reported from islands southeast of Misool which contain the larger benthic foraminifera *Lockhartia* and *Discocyclina* indicating water depths between 20m and 50m during Paleocene to Early Eocene (Belford, 1991).

Our reconstructions support interpretations of Norvick et al. (2003) and Golonka et al. (2009) where shallow water carbonates occur along southern edge of New Guinea margin and deep water settings along the northern margin. However, the position of Norvick et al.'s (2003) Bird's Head landmass is hereby reinterpreted as isolated shallow water regions where the Waripi Formation in the Salawati basin area consists of oolitic and bioclastic shoal limestones.

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. 6K). 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 and more shallow water areas developed within the central Bird's Head (Fig. 6L). This is supported from review of 51 wells, examination of nine outcrop samples and distribution of the Faumai Limestone (Fig. 6L). There are no palaeogeographic maps of this time interval produced by Visser and Hermes (1962) or Norvick et al. (2003); however our reconstructions broadly support the Early Eocene interpretation of Brash et al. (1991) and Golonka et al. (2009) of pelagic carbonates in the Bird's Neck at this time. This is supported by presence of carinate planktonic foraminifera observed in outcrop samples.

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 alveolinids including *Alveolina globosa*, *A*. *laxa, A*. *moussoulensis* and *A*. *subpyrenaica*, and larger benthics including *Asterocyclina* spp., *Discocyclina ranikotensis*, *Cuvillierina* spp. and *Daviesina* spp. (Fig. 9). 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 from limestone clasts in a Pleistocene conglomerate collected on the east coast of the Wandaman Peninsula (Fig. 6L). 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 Early Eocene age clasts within a Pleistocene age conglomerate from the Wandaman Peninsula also suggest water depths greater than 100m during the Early Eocene (Fig. 6L). 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. 9).

4.13 Middle - Late Eocene

The lowest Paleogene relative sea-level occurred across much of western New Guinea during the Middle to Late Eocene. Shallow water areas were prevalent across the central Bird's Head and Seram, and extended throughout the southern Bird's Neck and Body (Fig. 6M). This is supported from review of 61 wells, examination of 13 outcrop samples and distribution of units of the NGLG observed to contain Middle to Late Eocene aged microfaunal assemblages (Fig. 6M). Our reconstructions broadly support with Visser and Hermes (1962), Norvick et al. (2003) and Golonka et al. (2009) on widespread shallow water carbonate deposition across the majority of western New Guinea during the Middle to Late Eocene. In particular, our reconstructions agree with Visser and Hermes' (1962) interpretation of the shape and bathymetry of an east-west oriented swathe of shallow water across the centre of western New Guinea, where limestones dominated by *Alveolina* and *Lacazinella* occur, and deep water around the Bird's Neck. Our reconstructions refine Visser and Hermes' (1962) palaeogeographic interpretation of open marine facies close to the Fakfak region of the Bird's Head and Wandamen Peninsula (Fig. 6M).

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. 6M). 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, Aum-1, Boka-1X, Rawarra-1, Sago-1, Sebyar-1 and TBE-1X in particular. Bathymetric gradients away from the shallow water platforms drop to depths approaching 50m (Fig. 6M) 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 East

Misool-1, Soeaboor-1, Steenkool-1 and Tarof-2. Deep water facies are interpreted in the Onin wells based on the presence of *Acarinina* spp., *Globigerinatheka* spp. and *Morozovella* spp.

Interpretations from well data are supported by outcrop evidence along the western coastline of 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. 10). 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. 6M), 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, although the Wandaman samples were collected from a Pleistocene conglomerate and are likely transported. Samples here contain a mixture of globular planktonic foraminifera including *Acarinina bullbrooki*, *A*. *decepta*, *A*. *pentacamerata*, *A*. *primitiva*, *A*. *pseudotopilensis*, *Globigerinatheka* sp., *Subbotina eocaenica* and carinate forms including *Morozovella aragonensis* and *M*. *crassata* (Fig. 10).

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 & 10). 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 Apauwar-1, Muwar-1, and Niengo-1 in the Mamberamo region.

4.14 Oligocene

Relative sea-level rose across western New Guinea during the Oligocene. Palaeogeographic reconstructions of this time interval are based on review of 43 wells, examination of six outcrop samples and distribution of the Sirga Formation (Fig. 6N). There are no palaeogeographic maps of this time interval produced by Visser and Hermes (1962), although our reconstructions loosely support Brash et al.'s (1991) and Norvick et al.'s (2003) interpretations of a terrestrial area in the southern Bird's Neck deepening towards the northeast. However, Norvick et al. (2003) interpret an emergent region in the central Bird's Head although evidence from outcrop samples in this region support the Golonka et al. (2006; 2009) model of shallow water settings in the region at this time (Fig. 6N).

The southern landmass is surrounded by shallow bodies of water based on the presence of *Austrotrillina* spp. in several wells including ASA-1X, ASF-1X and ASM-1X (Fig. 6N). Occasional reefal build-ups are interpreted farther north where *Nummulites* spp are recorded from TBE-1X (Fig. 6N). Water depths up to 50m, extensive around the southern Bird's Head and Neck (Fig. 6N), are denoted by the presence of larger benthic foraminifera including *Cycloclypeus* spp., *Heterostegina borneensis*, *Operculina* spp. and *Pararotalia* spp. Moderate water depths are also interpreted in the Salawati basin area primarily from reports of *Heterostegina borneensis* in wells in this region (Visser and Hermes, 1962). Deeper water areas (Fig. 6N) are interpreted 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, and Onin South-1X.

Six samples of Early and Late Oligocene age were collected from the west coast of Cenderawasih Bay (Fig. 6N). 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 also observed in sedimentary lenses of the Arfak Volcanics of the eastern Bird's Head and Auwewa Formation on Supiori (Fig. 6N). 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*. However, these are found east of the Ransiki Fault (Fig. 1) and may indicate deeper water depths away from the current setting and juxtaposed against more shallow water rocks through movement along this fault.

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. 6O). This is supported from review of 95 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; Brash et al., 1991). 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.

Our interpretations broadly support interpetations of Visser and Hermes (1962) and Golonka et al. (2006; 2009) with the presence of a widespread shallow water, sometimes reefal, carbonate platform dominated by larger benthic foraminiferal limestones across much of western New Guinea, including carbonate build-ups and patch-reefs in the Salawati basin area (Gibson-Robinson and Soedirdja, 1986). However, we refine the area mapped by Visser and Hermes (1962) and Golonka et al. (2006, 2009) south of New Guinea due to a greater number of data points specific to New Guinea and new wells being drilled in the region since 1962.

A broad platform populated by reefal build-ups extending from the western Bird's Head to the Bird's Body (Fig. 6O) was interpreted from 90 wells. These wells intersect 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. This platform was surrounded by a body of water no greater than 50m in depth (Fig. 6O) based on the presence of the larger benthic foraminifera *Operculina* spp., *Heterostegina* spp. and *Cycloclypeus* spp. Rare deeper water sediments of this age occur Seram where they contain 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 6O, 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* (*Nephrolepidina*) *brouweri*, *L*. (*N.*) *isolepidinoides*, *L*. (*N.*) *nephrolepidinoides*, *L*. (*N.*) *oneatensis*, *L*. (*N.*) *stratifera*, *L*. (*N.*) *sumatrensis*, *Heterostegina borneensis*, *Miogypsina intermedia*, *M*. *kotoi*, *M*. *tani*, *Miogypsinoides bantamensis*, *Mdes*. *dehaarti*, *Miogypsinodella primitiva*, *Miolepidocyclina*, *Operculina* sp. and *Spiroclypeus tidoenganensis* (Fig. 11).

4.16 Middle Miocene

A 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. 6P), supporting interpretations of Brash et al. (1991). 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). This is supported by evidence from 95 wells and 42 outcrop samples analysed by this study.

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. 6P). A narrow moderate water depth carbonate platform developed on western and southern margin of Bird's Head and Neck (Fig. 6P). This broadly supports Brash et al.'s (1991) interpretation of platform carbonate in the southern margin of the LFTB and pelagic carbonates to the northeast.

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. 6P). 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* (*N.*) 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. 6P), 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* (*N.*) *brouweri*, *L*. (*N.*) *ferreroi*, *L*. (*N.*) *omphalus*, *L*. (*N.*) *verbeeki*, miogypsinids including *Miogypsinoides indica*, *Miogypsina cushmani*, *M*. *intermedia*, *M*. *kotoi*, *M*. *regularia* (Fig. 12).

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. 6P). 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*, *G*. *trilobus*, and rare *Globorotalia* spp. (Fig. 26).

4.17 Late Miocene

Relative sea-level continued to rise during the Late Miocene so that water depths greater than 100m were widespread across much of the present day western New

Guinea (Fig. 6Q). Deep water facies rocks are represented by the Befoor and Klasafet Formations of the Bird's Head and Neck, encountered in 112 of the reviewed wells and in 24 outcrop samples (Fig. 6Q). Visser and Hermes (1962) and Golonka et al. (2006, 2009) interpret an increase in basinal settings filled by deep water sediments across much of the Bird's Head. Small reefal areas, much reduced in size from the Early Miocene, are interpreted by Visser and Hermes (1962) in the western Bird's Head although we interpret slightly deeper water in these areas from predominantly wireline log responses from Salawati and Bintuni basins. Norvick et al. (2003) also interpret deep water sedimentation in the Bird's Neck and Salawati basin together with Vincelette (1973), Redmond and Koesoemadinata (1976), Collins and Qureshi (1977) and Gibson-Robinson and Soedirdja (1986). Our reconstructions differ, however, with Norvick et al. (2003) who interpret a widespread shallow water carbonate platform through the centre of the Bird's Head and Neck in the Late Miocene based on the presence of Kais platform limestones, although we interpret the Kais Limestones to be Early to Middle Miocene in age.

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. 6Q), 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 based on evidence from 101 wells and 29 outcrop samples (Fig. 6R). Deep water facies are also 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. 6R). Water depths in excess of 50m are recorded from wells across western New Guinea 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 wells to the south and west of the Bird's Head (Fig. 6R). 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. 6R). Shallow water facies, interpreted as back-reef lagoons, to the east of the Bird's Head (Fig. 6R) 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. 6R). 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 resulted in more extensive and frequent shallow water areas interpreted across the region by the Late Pliocene (Fig. 6S). This is supported by review of 98 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. Several areas of the Bird's Head, Neck and Body were submerged beneath waters no greater than 50m and localised areas were subaerially exposed close to the Salawati and Bintuni basins (Fig. 6T) as a precursor to the present day topography of the island of New Guinea. Our reconstructions are based on evidence from 43 wells and five outcrop samples is similar to Visser and Hermes' (1962) interpretation of New Guinea in the Pleistocene.

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. 6T). At this time Cenderawasih Bay itself became a distinct deep water feature filled by pelagic carbonates comprising planktonic foraminiferal packstones.

Only five samples were collected of Pleistocene age (Fig. 6T). 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. 6T). 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. 6T). 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. Discussion

5.1 Temporal Trends

Through the reconstruction of palaeodepositional environments using microfossil assemblages, temporal trends of relative sea-level change can also be deduced. Figure 13 displays a localised relative sea-level curve for the Bird's Head region from the Silurian to Pleistocene, based on the average water depth across western New Guinea at a given time (Fig. 13).

The second highest global 1st-order sea-level highstand for the Paleozoic occurred during the Silurian (Ross & Ross, 1988; Golonka, 2006) matching observations of palaeobathymetries in western New Guinea at this time. Relative sea-level fall from the Silurian to Devonian saw the replacement of deep water settings to terrestrially dominated environments persisting from the Permian to Early Jurassic (Fig. 13). Transgression throughout the Middle Jurassic and into the Cretaceous resulted in peak Mesozoic relative sea-level by the Late Cretaceous (Fig. 13), the time of maximum global sea-level during the Phanerozoic (Golonka et al., 2006), 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 carbonate 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. This collision caused sub-aerial erosion of Paleogene sediments in some areas forming a regional Early Miocene unconformity (Gold et al, 2014; Fig. 2). Collisional uplift within other areas, resulting in regional relative sea-level fall (Fig. 13), 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 Burdigalian (Gold et al., in review; Fig. 13). Relative sea-level rise reached its peak in the Late Miocene, possibly correlating with the global Tor1 flooding event (Hardenbol, 1998; Gradstein et al., 2012; 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. 13), leaving western New Guinea sub-aerially exposed as we know it today.

The regional Bird's Head relative sea-level curve is similar to that of published global sea-level curves (Haq and Al-Qahtani, 2005; Müller et al., 2008; Snedden and Liu, 2010) from the Silurian to Paleocene (Fig. 13). This implies that that the primary control on relative sea-level change throughout this time is eustatic. However, there are disparities between the curves from the Early Eocene to Oligocene (Fig. 13). This suggests that the primary control on relative sea-level change is more localised at this time and may be attributed to tectonic effects of regional subsidence and uplift and/or environmental controls influencing sedimentation rates. Following arc-continent collision in the Early Miocene the regional relative sea-level curve of the Bird's Head returns to recording the signal of global eustatic sea-level change (Fig. 13).

5.1 Comparisons with computer models

Our palaeogeographic reconstructions broadly support, and build upon, previously published palaeogeographic maps of New Guinea based on empirical data (e.g. Visser and Hermes, 1962; Audley-Charles, 1965; 1966; Brash et al., 1991; Golonka, 2006; 2009) but differ to computer modelled global and regional palaeogeographies (e.g. Zahirovic, 2014; 2016, Heine et al., 2015; Leprieur et al., 2016). This is attributed to the replication of parameters unsuitable for tectonically complex regions such as Southeast Asia.

Most computer models use global eustatic sea-level curves (Haq et al., 1987; 2014, Haq and Al-Qahtani, 2005; Haq and Shutter, 2008; Müller, 2008; Snedden and Liu, 2010) as a basic parameter for their models and apply this to global basins, including those in Southeast Asia. The sea-level curves of Haq et al. (1987) and Haq and Al-Qahtani (2005), in particular, are based on observations from the Arabian platform. This region has a remained a relatively stable homoclinal carbonate ramp since the XXXX, thus preserves a good record of facies changes up and down the ramp enabling the determination of past relative, and regional, sea-level change.

Heine et al (2015) concluded that calculations of land areas relative to the total area of continental crust extracted from the empirical data of Smith et al. (1994) and Golonka et al. (2006) produced palaeoshoreline maps that matched sea-level curves of Haq & Al-Qahtani (2005) and Müller (2008). The Smith et al. (1994) and Golonka et al. (2006) models have a sparse dataset in Southeast Asia, with no data points for New Guinea or most of Indonesia except Kalimantan. Therefore, subtle regional deep marine incursions and development of widespread carbonate platforms are not recorded in palaeogeographic reconstructions. Lepreiur et al. (2016) take a different approach to mapping the development of carbonate platforms in Southeast Asia by using a mechanistic model of species diversification combined with a model of synthetic paleobathymetry estimates to map the global spatial distribution of biodiversity hotspots since the Cretaceous. This approach models the migration of new species and biodiversity hotspots through time, moving east from the western Tethys through the Arabian peninsula and west Indian Ocean, arriving in the Indo-Pacific during the Miocene (15-5 Ma)(Leprieur et al., 2016). However, our models show that western New Guinea was a biodiversity hotspot where carbonate platforms flourished during the Middle-Late Eocene. Leprieur et al. (2016) remark that ecological diversification is controlled by the availability of tropical reef habitat through time. We argue that more tropical reef habitat was available earlier, during the Eocene in particular, than suggested by Leprieur et al. (2016) as indicated by the regional relative sea-level curve of Figure 13. Widespread carbonate platform development in New Guinea during the Eocene may be controlled by regional tectonism and/or favourable environmental conditions that permitted high rates of carbonate production.

Although our palaeogeographic reconstructions do record changes in the long-term eustatic sea-level signal for parts of the Phanerozoic, it is shown to diverge from this trend between the Eocene and Oligocene (Fig. 15). Zahirovic et al. (2016) and Yang et al. (2016) note that flooding in the Sundaland platform of Indonesia increases during the Eocene while the fraction of continental crust experiencing marine inundation decreases globally with long-term eustatic sea level fall (Haq and Al-Qahtani, 2005; Müller, 2008; Snedden and Liu, 2010; Heine et al., 2015). The mechanism for this divergence from global sea-level curves in southern Sundaland is interpreted to be due to the downwelling of mantle causing regional subsidence (Yang et al., 2016). This reinforces the interpretation that the use of published global sea-level curves is not appropriate for regions such as Southeast Asia where complex tectonism and favourable environmental conditions for carbonate production, having been situated in low latitudes since the at least the Triassic (Audley-Charles, 1966), may be greater controls on palaeogeography than eustatic factors.

Often computer modelled palaeobathymetries (e.g. Müller et al., 2008) are too coarse to be used as parameters in modelling subtle changes in palaeogeography at a regional scale. These models have the capability of computing global bathymetric changes in hundreds to thousands of metres water depth, however the use of palaeontological and sedimentological data, as shown by this study, can model changes in bathymetry at a scale from a few tens to hundreds of metres. Therefore, we interpret that bathymetric models are more precise in reconstructing regional paleogeography using empirical data and sea-level fluctuations in tectonically complex areas should not be related to global eustacy curves and relative sea-level curves should be established that are specific to the region (e.g. Fraser et al., 1993).

6. Conclusions

Empirical data from well 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. Peaks in relative sea-level are interpreted to have occurred in the Late Cretaceous and Late Miocene. These regional relative sea-level highs record a signal corresponding to peaks in the long-term trend of eustatic sea-level change Haq and Al-Qahtani, 2005; Müller, 2008; Snedden and Liu, 2010). Divergence from the long-term global eustatic sea-level trend during the Eocene to Oligocene is attributed to regional tectonism and/or environmental factors.

This study refines previous published palaeogeograpghic maps of western New Guinea using empirical data (Visser and Hermes, 1962; Audley-Charles, 1965; 1966; Brash et al., 1991; Golonka, 2006; 2009). The use of empirical data is shown to be more robust in determining regional changes in relative sea-level than computer models that use global eustatic sea-level curves as parameters (e.g. Zahirovic, 2014; 2016, Heine et al., 2015; Leprieur et al., 2016).

If we consider that the latitude and position of New Guinea relative to Australia has not changed considerably since the Triassic then our palaeogeographic reconstructions south of the Australia-Pacific suture from the Triassic onwards are relatively robust. We are also confident in the robustness of the reconstructions using post-collisional stratigraphy of the region. 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.

Acknowledgments

This work was supported by the Southeast Asia Research Group at Royal Holloway, funded by a consortium of oil companies. We thank our fieldwork counterparts from the Institut Teknologi Bandung as well as John Decker, Phil Teas, Angus Ferguson and Farid Ferdian (all previously of Niko Asia), together with the crew of the Shakti live-aboard vessel for assistance during fieldwork. Various staff members and postgraduate research students at Royal Holloway, University of London also helped. We particularly like to thank Robert Hall, Benjamin Jost and Max Webb for commenting on an earlier version of this manuscript.

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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. Location of wells and reefs reinterpreted by this study. References for public domain data listed in Table 1.

Figure 6. Palaeogeographic reconstructions of western New Guinea from the Silurian to Pleistocene. Based on evidence from public domain well data, biostratigraphic reports, regional geology, sedimentological interpretations and new outcrop data.

Figure 7. 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 8. 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), *Contusotruncana fornicata* (*C.f*), *Globotruncana arca* (*G.a*), *Globotruncana bulloides* (*G.b*), *Heterohelix globulus*. (*H.g*).

Figure 9. 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*), *Alveolina moussoulensis* (*A.m*), *Discocyclina ranikotensis* (*D.r*), *Alveolina globosa* (*A.g*), *Planostegina* spp. (*O*), *Daviesina* spp. (*D*), *Nummulites* spp. (*N*), *Acarinina* spp. (*Ac*), *Globigerinatheka* spp. (*Gt*), *Morozovella* spp. (*Mz*).

Figure 10. 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*), *Pellatispira* spp. (*Pt*), *Acarinina* spp. (*Ac*), *Globigerinatheka* spp. (*Gt*), *Acarinina pentacamerata* (*A.pe*), *Acarinina bullbrooki* (*A.b*), *Subbotina* spp. (*Sb*), *Acarinina primitiva* (*A.pr*), *Daviesina* spp. (*D*), *Morozovella* spp. (*Mz*).

Figure 11. 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*), *Planorbulinella larvata (P.l), Spiroclypeus tidoenganensis* (*S.t*), *Eulepidina* spp. (*Eu*), *Miogypsina* spp. (*Mg*), *Amphistegina* spp. (*Am*), *Heterostegina* spp. (*Hs*).

Figure 12. 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* quadrilobatus (*G.g*), *Orbulina universa* (*O.u*).

Figure 13. Relative sea-level curve based on average bathymetry in western New Guinea compared to global sea-level curve of Snedden and Liu (2010). Two main transgressive-regressive cycles are interpreted with peak relative sea-level occurring during the Late Cretaceous and Late Miocene.