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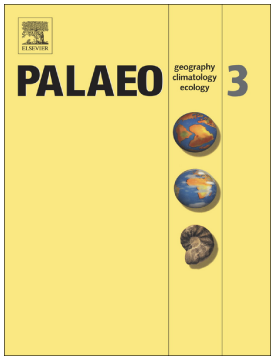

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Late Cenozoic palaeogeography of Sulawesi, Indonesia

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ABSTRACT

Sulawesi has a remarkable biodiversity, an unusually rich endemic fauna, and is the largest island in Wallacea, just west of the Wallace Line. Alfred Russel Wallace himself suggested it could perhaps be the most remarkable island on the globe because of its peculiar fauna. It was home to extinct fossil fauna such as dwarf proboscideans, records significant Pleistocene faunal turnover, and evidence of early human occupation suggests an important role in hominid migration through the Sunda-Sahul region. Information on Neogene palaeogeography is essential for understanding biogeographic patterns, biodiversity and faunal changes. New palaeogeographic maps reflecting recent work on Sulawesi's complex geology and changes in tectonic interpretations are presented for intervals from the Early Miocene to Pleistocene, at 20, 15, 10, 8, 6, 5, 4, 3, 2, and 1 Ma. Additional maps illustrate the effects of glacially-driven sea level change in the last 1 Myr. They are based on a field-based investigation of sedimentary rocks in Sulawesi, accompanied by palaeontological, petrological and heavy mineral studies and U-Pb dating of detrital zircons, to date and determine depositional environments. The new results have been supplemented by re-evaluation of previous studies, including reports from oil company wells and seismic lines. Igneous rocks provided ages, indications of surface environment of eruptions, and location of magmatic activity. For most of the Neogene from the Early Miocene Sulawesi was a shallow marine area with a number of small islands, surrounded by relatively deep marine areas. Deep inter-arm bays began to form in the Late Miocene and the islands became larger. The most significant palaeogeographic change began in the Pliocene with an increase in the area and elevation of land accompanied by major subsidence of the inter-arm bays. The separate islands gradually coalesced in the Pleistocene to form the distinctive K-shaped island known today.

Keywords

Neogene; Uplift-subsidence; Land-sea; Landscape; Islands

1. Introduction

Sulawesi (formerly called Celebes) is the eleventh largest island in the world and the fourth largest in SE Asia after New Guinea, Borneo and Sumatra. It has four long peninsulas named the North, East, South and SE Arms that form a distinctive K shape (Fig. 1). They are separated by deep marine bays: Gorontalo Bay, Tolo Bay, and Bone Bay. To the west, the Makassar Strait separates Sulawesi from Borneo.

Sulawesi has a remarkable biodiversity and complex geology that has attracted biologists and geologists to study the area since the 19th century (e.g. Wallace, 1860, 1869; Sarasin and Sarasin, 1901). Biogeographically, Sulawesi is situated in a transitional zone between faunas of Asian and Australian origin (Wallace, 1860; Weber, 1902; Mayr, 1944), now known as Wallacea (Dickerson, 1928). It is the largest island in Wallacea with an unusual number of endemic species (Myers et al., 2000; Whitten et al., 2002; Lohman et al., 2011; Stelbrink et al., 2012). Geologically, Sulawesi is situated close to the junction of the Eurasian, Australian and Pacific plates in a complex convergent region (e.g. Hamilton, 1979). Plate tectonic hypotheses and tectonic reconstructions (e.g. Rangin, 1990; Daly et al., 1991; Hall, 1996) for many years interpreted the region in terms of multiple collisions and suggested to some biogeographers that pre-collision faunas and floras in SE Asia might have been supplemented by arrivals from the east carried on crustal fragments, perhaps sliced from New Guinea as suggested by Hamilton (1979), or dispersed via Pacific island arcs (e.g. de Boer and Duffels, 1996; Michaux, 1996; Holloway and Hall, 1998). Recent studies have continued to link biogeographic patterns and geology (e.g. van den Bergh et al., 2001; Evans et al., 2003a,b; Merker et al., 2009; Stelbrink et al., 2012; Evans, 2012; Driller et al., 2015; Mokodongan and Yamahira, 2015). But there have been significant changes in our understanding of Sulawesi's geology in recent years. The importance of Neogene extension has become clear (Hall and Wilson, 2000; van Leeuwen et al., 2007; Spencer, 2010, 2011; Hall, 2011) as have the timing and speed of change which led to the formation of the island's high mountains and deep basins. The geological interpretation of the region in terms of multiple collisions of tectonic slices moving from the east has been significantly modified, and biogeographic hypotheses based on these models thus require reconsideration.

Sulawesi is a large island, with an area similar to that of the British Isles, but in comparison is considerably understudied. Despite the long history of geological work our knowledge of the island remains limited. Nevertheless, we believe we can now improve previous interpretations and have attempted here to meet the challenge of drawing palaeogeographical maps at closely spaced time intervals to illustrate how and when the present-day landscape formed, and to provide an improved basis for biogeographical interpretations of Sulawesi.

2. Geological and biogeographical background

The great 19th century naturalist Alfred Russel Wallace considered the island of Sulawesi "in many respects the most remarkable and interesting in the whole region and perhaps on the globe" for "its peculiar fauna" (Wallace, 1876). He had already recognised the importance of geology for understanding biogeographical patterns in the region (Wallace, 1869). He interpreted an Asian continent, with a transition to the southeast into islands which almost reached the remnants of a great southern continent, now disappeared, and observed that "it will be evident how important an adjunct Natural History is to Geology". Wallace had a dynamic view of the region and speculated on how a former wide ocean might have been modified to form the modern archipelago but it was to be another century before geologists were able to offer better explanations. The plate tectonic revolution of the late 1960s in the earth sciences changed the paradigm of fixed continents and led to renewed interest in interpreting biogeographical patterns in terms of geological change (e.g. Audley-Charles, 1981; Whitmore, 1981). Wallacea is now understood as a complex convergent region in which subduction and collision continue today.

However, tectonic reconstructions and maps of continental and island arc fragments or terranes have often misled biogeographers because tectonic elements do not always translate simply into geographical features such as land and sea, or topography and bathymetry. Attempts have been made to remedy this (e.g. Hall, 1998, 2001; Moss and Wilson, 1998) by drawing interpretations of palaeogeography on plate reconstructions, but intervals in time between maps were large (5 Myr or more) and the area covered also very large. Maps are required at closer time intervals, but producing them can be very difficult. Much of the geological record is based on marine sediments, for which dating from fossils may provide very detailed time resolution, and interpreting bathymetry and environment of deposition is relatively straightforward, but there are much greater problems in deciphering and interpreting the geography of land areas, where there is commonly no direct record due to erosion or non-deposition, fossils are absent or uncommon in such terrestrial rocks that were deposited and preserved, and inferring topography is a major challenge. Nonetheless, regional palaeogeographical maps (Hall, 2009; 2012b, 2013; Morley and Morley, 2013) have improved.

At the same time, tectonic interpretations of the region have changed and it has become clear that plate convergence has not resulted simply in subduction and collision (e.g. Hall, 2011, 2012b, 2017a; Pownall et al., 2014; Advokaat et al., 2017). In eastern Indonesia young extension (e.g. Spencer, 2010, 2011; Pownall et al., 2013, 2016), mainly driven by subduction (Spakman and Hall, 2010) has dramatically changed the geography of the region. Deep basins formed at the same time as mountains rose in the last few million years. Interpretation of the ages of events has also changed with improved dating.

This study began with the aim of improving the stratigraphy and understanding the significance of the rocks assigned to the Celebes Molasse, a term introduced in one of the earliest studies of Sulawesi geology, by Sarasin and Sarasin (1901), for young clastic sediments found throughout the island. The term was later applied to almost all sedimentary rocks that unconformably overlie pre-Neogene rocks. Its use gives an impression of synchronous and widespread post-orogenic siliciclastic deposition in the Miocene and Pliocene across Sulawesi (e.g. van Bemmelen, 1949; Kündig, 1956) whereas many of the Neogene sediments of Sulawesi are poorly known and not well dated. The Neogene history of Sulawesi began with collision that caused uplift and widespread erosion, although views on what was colliding, with what, and when, have changed (e.g. Audley-Charles, 1974; Katili, 1978; Hamilton, 1979; Rangin et al., 1990; Daly et al., 1991; Smith and Silver, 1991; Hall, 1996, 2002, 2012a). Here we consider the Celebes Molasse as deposits that post-date the major Early Miocene collision of a promontory of Australia, the Sula Spur (Klompé, 1954), with the SE Asian margin in Sulawesi (Hall, 1996, 2002, 2012a). These sediments are not simply the product of collision and uplift, but they provide a key to interpreting the Neogene history and the changing palaeogeography of Sulawesi.

3. Data sources and revised stratigraphy

Fieldwork was conducted between 2012 and 2015 in the SE, East and North Arms, in the Neck and in Central Sulawesi. A total of 413 field locations and 228 samples were analysed. Field observations, including sedimentary logs, palaeocurrent measurements, and details of lithologies, provide information on depositional processes and environments. Palaeontological analyses (e.g. molluscs, foraminifera, nannofossils and pollen) provide age ranges as well as information about the depositional environment. Provenance studies of sediments (e.g. based on light and heavy minerals and U-Pb dating of detrital zircons) give information about sediment sources and may provide maximum depositional ages.

Most of western Sulawesi, the North Arm, and the South Arm of Sulawesi were not visited during this study, but previous publications and unpublished reports, including oil company reports on wells and seismic lines, were used. Results from previous studies, both onshore and offshore, were re-evaluated and integrated with those from new investigations and subsequent laboratory studies, particularly those conducted in recent years by the SE Asia Research Group at Royal Holloway University of London in collaboration with Indonesian collaborators (Ferdian et al., 2010; Cottam et al., 2011; Watkinson, 2011; Watkinson et al., 2011; Pholbud et al., 2012; Camplin and Hall, 2014; Hennig et al., 2014; Pezzati et al., 2014; White et al., 2014, 2017; Advokaat, 2015, 2017; Hennig, 2015; Hennig et al., 2016, 2017; Nugraha, 2016; Rudyawan, 2016; Pezzati, 2017) and others (van Leeuwen and Muhardjo, 2005; van Leeuwen et al., 2007, 2010, 2016). Sample ages and data were

plotted using GIS software and, with a revised Neogene stratigraphy for Sulawesi (Fig. 2), provide the basis for the palaeogeographic maps.

4. Constructing the palaeogeographic maps

The maps were produced in five steps from (1) a tectonic base map, (2) a geological map showing the distribution of rocks of different ages and types, (3) georeferenced location of dated samples, and (4) interpretation of environments of deposition. The final step was to map the distribution of different bathymetric and topographic intervals, classified into marine abyssal (below 4000m deep), bathyal (4000m to 200 m deep) and shelf (200m to sea level) categories; and terrestrial coast to lowland (sea level to 1000 m), highland (1000m to 2000m), and very high mountain (2000m and above) terrains. Although the palaeogeographic maps are presented from oldest to youngest, they were constructed by working backwards from the present. The younger maps have fewer inferences and better topographic and bathymetric constraints. For example, the present topography and bathymetry (Fig. 1) provide a constraint when estimating topographic height and water depth for the 1 Ma map using reasonable assumptions of uplift and subsidence rates. The 1 Ma map similarly provides a constraint on the 2 Ma map, and so on.

4.1. Tectonic base maps

The tectonic reconstructions are based on Spakman and Hall (2010) and Hall (2012a) but have been modified to incorporate results from our recent studies cited above which have significantly improved our knowledge of Sulawesi geology on land and offshore, and timing of events such as fault movements and uplift/subsidence. The major fault zones (Fig. 1 and Fig. 3) are reasonably well known, with the exception of the Lawanopo Fault zone. However, despite uncertainties in estimating amounts and timing of displacements on these faults it is important to recognise that all of them have a Neogene history of significant vertical (normal/extensional) and lateral (strike-slip) displacements but there is no evidence to indicate that any have a history of convergence. In other words, during the Neogene, and especially during the last 10 Myr, Sulawesi should not be seen as the product of assembly of widely separated “mini-plates” but more as a single region in which different parts have moved laterally with respect to one another due to regional tectonic forces, primarily subduction in the Banda region and Celebes Sea, resulting in extension, ocean formation, subsidence and uplift. If these major fault zones, and other geological contacts, have acted as biogeographic boundaries it must be because the consequences of fault movements, such as juxtaposition of contrasting rock types, major elevation changes, changes in rainfall, drainage, soil and vegetation, created or diminished barriers, or affected links between different parts of the island(s).

Evidence from dating of igneous and metamorphic rocks with ages of 2-3 Ma now exposed at elevations of more than 1 km, and inferences from observations of former carbonate reefs now at

depths between 1 and 2 km with no sediment cover, indicate that some landscape changes have been extremely rapid. Nonetheless, the present mountains with elevations of up to 3 km height could not have risen from sea level in 1 million years, nor could reefs now at water depths of up to 2 km have subsided in a similar time interval. Based on dating and uniformitarian assumptions the palaeogeographic maps can be integrated with other geological data to interpret landscape evolution back to 6 Ma at 1 Myr intervals with gradually decreasing confidence. Before that, the palaeogeographic maps become less certain and less detailed reflecting a diminishing geological record, fewer dates and other uncertainties. The limited data available means that only 2 Myr intervals between maps are justified to 10 Ma, and 5 Myr intervals for the earlier Neogene back to 20 Ma.

5. Interpretations from the geological record

Palaeogeographic interpretations can be made with reasonable confidence when there is a rock record, such as sediment accumulations or volcanic products. The geological map (Fig. 3) shows where there are Neogene rocks. It is immediately obvious that there are none in many parts of Sulawesi. Less certain, indirect inferences from provenance information, igneous rocks and older basement rocks are needed to interpret features of the landscape when there is no rock record.

5.1. When there are Neogene rocks

Where Neogene rocks are preserved (Fig. 3), palaeontological analyses provide age ranges as well as information about the environment of deposition. Relatively precise ages can be commonly be obtained from marine sedimentary rocks. In addition, minerals such as glauconite can give marine depositional information. In contrast, terrestrial and marginal marine sediments typically have wider age ranges when fossils are present, or may be dateable only from limits provided by other rocks (e.g. marine sediments above or below, or volcanic intercalations). The age range of each sample (e.g. age limits of a foraminifera stage or nannofossil zone, or age plus or minus the error for an isotopic age) was used when plotting samples on maps of different ages. Terrestrial sediments are less easy to date but they can provide information about environments. For example, fluvial sediments are deposited downstream from the sediment source and upstream from their marginal marine and marine time equivalents. Thus, Pliocene deposits in the southern SE Arm indicate SE-flowing rivers and imply elevated regions further north.

5.2. When there are no Neogene rocks

Parts of the landscape such as inaccessible deep-water areas or mountains present different problems for palaeogeographic reconstruction. For the oceanic areas around Sulawesi the solution is relatively simple. The areas of oceanic crust to the north (Celebes Sea), northeast (Molucca Sea) and east of Sulawesi (North Banda Sea) imply long-lived deep sea environments from the time they were

formed. Oceanic crust typically forms at depths of about 2.5 km below sea level and subsides with age. The Celebes Sea is Eocene (Weissel, 1980; Silver and Rangin, 1991) and the North Banda Sea formed between 12 and 7 Ma (Hinschberger et al., 2000). Once these oceanic areas formed they would always have been deep. The age of the Molucca Sea is uncertain as it is covered with thick sediment, but most of it has been subducted to the west and east beneath the Sangihe and Halmahera arcs which are active today. The ages of volcanic rocks in those arcs indicate a deep marine environment to the northeast of Sulawesi throughout the Neogene.

Mountains present another problem. In areas such as large parts of the Neck and Central Sulawesi where deep crustal rocks are now at the surface, the East Arm ophiolite, or metamorphic rocks of the SE Arm, it is difficult to assess past environments because there is no remaining sediment cover. However, erosional and depositional landscapes are linked by a sediment-routing system in which sediment was transported from a source hinterland to a basinal area (Allen, 2008). The erosional mountain landscape is a source area from which sediments were transported to rivers, coastal plains, deltas, shelves and deep seas. This inherently linked sedimentary system can be deduced from provenance studies of clastic rocks. Clastic rocks contain rock fragments and light and heavy minerals that act as fingerprints for source areas and so can help to reconstruct the erosional landscape. Provenance studies using light and heavy minerals and U-Pb dating of detrital minerals give information about source rock types, which can be used to indicate derivation from particular parts of Sulawesi at different times. For example, the East Arm and northern SE Arm have been the source of distinctive ultramafic rock and mineral detritus, certain types of metamorphic rocks are restricted to specific areas (e.g. blueschists and distinctive blue amphiboles, lawsonite and chloritoid in the SE Arm), and young granites are known from Central Sulawesi and the Neck. These source regions imply elevated areas in specific parts of Sulawesi at identifiable times. Dating of detrital zircons can indicate source regions, may provide a maximum depositional age of the sediment (especially if they are reworked from volcanic products) and can record the uplift/exhumation history.

Finally, there is a tectonic linkage of mountains and basins. In Sulawesi, Early Miocene collision of the Sula Spur created mountains and marginal foredeeps where sediment accumulated. Later Neogene extension that produced the North Banda Sea and the deep inter-arm basins also caused uplift on land. The contemporaneous uplift of mountains, basin subsidence, high erosion rates, and rapid deposition means that interpretations of areas that now lack Neogene sedimentary rocks may be possible from sedimentary and non-sedimentary rocks elsewhere. For example, young granitoid and metamorphic rocks form high mountains (up to ca. 3 km high) in NW Sulawesi. Rapid exhumation in the Neck and Central Sulawesi in the past 2.5 Myr (e.g. Spencer, 2010, 2011; Hennig et al., 2014, 2016, 2017; Hennig, 2015) is indicated by the exposure of such rocks with ages (U-Pb, Ar-Ar and U/Th-He) of 3.5 to 2.5 Ma. On the western side of the Neck they are overlain by granitoid and metamorphic-rich coarse alluvial deposits with a maximum depositional age from detrital zircons of

2.5 Ma (this study) which pass up into Pleistocene fluviatile sediments with nannofossils and alunite clasts dated as ca. 1.7 Ma (van Leeuwen and Muhardjo, 2005). Submerged pinnacle reefs in the centre of Gorontalo Bay (as deep as 2 km below sea level, but uncovered by clastic sediments) are interpreted to indicate subsidence contemporaneous with exhumation on land.

6. Palaeogeographical maps

Below we summarise the evidence and geological events relevant to the age of each map. Since these maps are intended for both geologists and biogeographers we attempt to include sufficient geological detail to make the maps comprehensible to a non-geologist but adequately supported by cited sources to make the basis for the interpretations clear to those more interested in the geology. The sources provide much more detail on the geology and the tectonic causes of geological change. Each map has an uncertainty that is difficult to display on the maps or quantify. We suggest, as a guide, to regard the maps of each age before or after a specific map as indicating the 90% confidence limit of that map. Thus for example, if an area is shown to subside to greater depths at 3 Ma the timing of subsidence could be considered as between 4 and 2 Ma. In some cases, for example where there are records from oil company wells, or for the most recent maps, it may be possible to be more precise than this, but in most cases, even with excellent dating, this is a fairly precise estimate of timing. However the uncertainty is assessed it is important not to take the maps literally but to consider them as an educated estimation of palaeogeography at a certain time. A qualitative guide to the confidence in each map is given by the number of data points plotted on the map, which is listed in the figure caption, and their distribution, which shows where the maps are well constrained and where boundaries are inferred with less certainty. Details of the data used in this study are in Nugraha (2016).

6.1. 20 Ma map

The Sula Spur collided with the North Sulawesi volcanic arc in the Early Miocene. By ca. 20 Ma, there was an elevated mountainous region, dominated by ophiolitic, principally ultrabasic, rocks in eastern Sulawesi due to this collision (Fig. 4A). This land was a major source for the oldest sediment fill (Pholbud et al., 2012; Pezzati, 2016) in western Gorontalo Bay which formed a foreland basin to the north of uplifted highlands. In the east Lower Miocene carbonates contain serpentine, olivine and chert grains (van der Vlerk and Dozy, 1934; Nugraha, 2016) and there was significant clastic input to Tolo Bay and the northern SE Arm from uplifted ophiolites in eastern Sulawesi. An elevated but lowland area in West Sulawesi is interpreted from the Tike-1 well in the lower Lariang Basin in which fine grained clastic sediments contain reworked Lower Miocene fossils (Calvert, 2000). Emergent areas in South Sulawesi are inferred from K-Ar dating of volcanic rocks (Sukamto, 1990; Bergman et al., 1996; Polvé et al., 1997; Elburg et al., 2003). The limited biostratigraphic data for the Early Miocene suggest a wide shallow marine area across most of South Sulawesi. Seismic and

field data from Bone Bay (Camplin and Hall, 2014) and South Sulawesi (Wilson, 1995, 2000; Wilson and Bosence, 1996) show rifting in a predominantly shallow marine environment.

6.2. 15 Ma map

In Sulawesi and further east (e.g. Pownall et al., 2013, 2014) there was widespread extension linked to both uplift and subsidence of parts of Sulawesi. It led later to spreading of the North Banda Sea (Hinschberger et al., 2003) ultimately driven by rollback to the ESE (Spakman and Hall, 2010; Hall, 2012a) of the Banda subduction zone.

A wide land area extending north and west from the East Arm (Fig. 4B) is inferred from an unconformity surface in eastern Gorontalo Bay (Pholbud et al., 2012; Pezzati, 2016) and marginal marine sediments in the southern East Arm (Davies, 1990; Hasanusi et al., 2004). There may have been some small land areas in West (and possibly North) Sulawesi due to uplift associated with magmatic activity recorded by igneous rocks (Sukamto, 1990; Bergman et al., 1996; Polvé et al., 1997; Elburg and Foden, 1999; Elburg et al., 2003). This is supported by Middle Miocene volcaniclastic debris penetrated by the Tike-1 well in the Lariang Basin of West Sulawesi suggesting terrestrial explosive volcanic activity (Calvert, 2000). Middle Miocene marine mudstones of West Sulawesi imply some low-lying emergent areas supplying sediment.

In southern Sulawesi, rifted basins developed in shallow to deeper marine settings in which Middle Miocene sediments were deposited. Lower Miocene carbonates in the South Arm were replaced by marine clastics (Grainge and Davies, 1985; Wilson, 1995, 2000; Wilson and Bosence, 1996). Turbidites and thick volcaniclastic deposits are known from the Bone Mountains (van Leeuwen et al., 2010). In the SE Arm a hiatus could mean that Middle Miocene sediments were eroded or simply never deposited. Thick laterite deposits in the northern part of SE Sulawesi which are now mined for nickel provide tenuous indications of prolonged emergence. Laterite formation is thought to require long periods of subaerial tropical weathering, although the times required are not known (Schellmann, 1983; Butt and Cluzel, 2013). A deep marine area in the southern part of Buton Island is inferred from deep-water foraminifera and nannofossils recorded in Middle Miocene sediments (Benteng-1 and Bulu-1S wells; Robertson Indonesia, 1989; Davidson, 1991).

6.3. 10 Ma map

By 10 Ma there was significant extension affecting many parts of Sulawesi and further east oceanic crust was forming in the North Banda Sea which was midway through its spreading phase (Hinschberger et al., 2003) linked to Banda subduction rollback (see Hall, 2012b, 2013).

Marine environments are inferred for northern Sulawesi (Fig. 5A) where there is a limited Neogene stratigraphic record, based on small exposures of shallow marine carbonates in the Togian Islands (Cottam et al., 2011), and interpreted from seismic lines crossing Gorontalo Bay (Pholbud et

al., 2012; Pezzati, 2016). The interpreted absence of siliciclastic sediments in Gorontalo Bay, and the presence of a deep-water area further north in the Celebes Sea, supports this inference. In the Tomini Basin of western Gorontalo Bay, carbonates prograded towards the basin centre indicating minor subsidence in the basin (Pholbud et al., 2012; Pezzati, 2016). In the eastern East Arm, shallow marine carbonate deposition above older marginal marine deposits indicate a reduced clastic input from the East Arm (Davies, 1990; Hasanusi et al., 2004).

Increasing magmatism probably caused uplift in West Sulawesi. Magmatism also occurred in South Sulawesi forming volcanoes (Sukamto, 1990; Bergman et al., 1996; Polvé et al., 1997; Elburg and Foden, 1999; Elburg et al., 2003) and produced volcanic detritus deposited in marine areas of Bone Bay, West and South Sulawesi (van Leeuwen, 1981; Grainge and Davies, 1985; Wilson, 1995, 2000; Calvert, 2000; Sudarmono, 2000). Despite magmatism, carbonates were still growing locally on the structural highs of the South Arm and possibly Bone Bay (Grainge and Davies, 1985; Wilson, 1995; Ascaria, 1997; Camplin and Hall, 2014). In the SE Arm, ultrabasic- and ophiolitic-rich siliciclastics were deposited in terrestrial to marine environments interpreted from Middle to Upper Miocene marine sediments penetrated by well BBA-1X (Sudarmono, 2000) and interpreted Upper Miocene seismic sequences in Tolo and Bone Bays (Rudyawan and Hall, 2012; Camplin and Hall, 2014). They must have been derived from a hinterland source in eastern Sulawesi. A deepening succession from sublittoral to upper bathyal in Buton Island suggests continuous subsidence during the Middle and Late Miocene (Wiryosujono and Hainim, 1975; Robertson Indonesia, 1989; Fortuin et al., 1990; Smith and Silver, 1991).

6.4. 8 Ma map

Subduction beneath the North Arm initiated at about this time (Advokaat, 2015; Hall, 2017b). During the early stages there was no subducted slab beneath the North Arm but there was some magmatism in the North Arm, accompanied by deepening and northward movement of material downslope at the southern margin of the Celebes Sea. The North Arm began to rotate towards the Celebes Sea.

Granitoid intrusions at a small number of locations in the central North Arm (Rudyawan, 2016) may have caused local emergence of land (Fig. 5B). The fact that carbonates were deposited in the surrounding area (NW Sulawesi, Tomini Basin of Gorontalo Bay, Togian Islands and parts of the East Arm) suggests relatively little volcanic activity. Renewed carbonate deposition in the southern East Arm (Davies, 1990; Hasanusi et al., 2004) suggests deepening in this area. Nearby land was reduced in area and probably separated from the SE Arm. Abundant K-Ar and zircon U-Pb ages in northern and southern West Sulawesi (Priadi et al., 1993,1994; Bergman et al., 1996; Polvé et al., 1997; Elburg et al., 2013; Hennig et al., 2015) indicate widespread magmatism and suggest increasing land area

associated with subaerial volcanism. Uplift is supported by the increasing proportion of marine gravity flow deposits containing volcanic lithic fragments in the west (Calvert, 2000).

In the East Sengkang Basin of eastern South Sulawesi, Upper Miocene Tacipi Formation pinnacle reefs (Grainge and Davies, 1985) mark onset of locally rapid subsidence followed by significant volcaniclastic input (van Leeuwen et al., 2010). These carbonates were contemporaneous with volcanic-rich siliciclastics of the upper Camba Formation (Grainge and Davies, 1985). Reworked volcanic fragments within these deposits were probably sourced from the north. The deep-water area of Bone Bay is thought to have extended further north between West and East Sulawesi. A northern semi-enclosed Bulupulu Sub-basin (Camplin and Hall, 2014) in southern Central Sulawesi was inferred from the Upper Miocene Bonebone Formation which contains abundant nannofossils of *Sphenolithus abies*. These Upper Miocene marine sediments were deposited in a submarine delta or fan setting. Heavy mineral analysis indicates that they were derived mainly from ultrabasic and basic rocks in East Sulawesi with a subsidiary metamorphic and volcanic contribution from West Sulawesi. In the SE Arm, the Pandua Formation was deposited in terrestrial (Abuki-1 well; Robertson Indonesia, 1989), through deltaic to marginal marine (southern SE Arm), and deep marine environments (Bone Bay, Buton; Wiryosujono and Hainim, 1975; Smith, 1983; Davidson, 1991; Fortuin et al., 1990; Smith and Silver, 1991; Camplin and Hall, 2014) and was sourced from ultrabasic rocks in the northern SE Arm. Local sources of metamorphic and Triassic-Jurassic sedimentary rocks in the southern East Arm increased in importance later in the Miocene (until ca. 6 Ma). The Tondo Formation of Buton was initially interpreted to have been derived locally from the interior of Buton Island (Smith, 1983; Smith and Silver, 1991). In contrast, Fortuin et al. (1990) suggested the Tondo Formation was derived from a larger source area based on the enormous amounts of coarse clastic sediments. This study supports the second interpretation since there are very limited ultramafic exposures in Buton Island but abundant ultrabasic and serpentinite rock clasts with chrome spinel grains in the Tondo Formation, like the Pandua Formation of the SE Arm, suggesting a common source further north where ultramafic rocks are widespread today.

6.5. 6 Ma map

By ca. 6 Ma extension in northern and central Sulawesi was driven by subduction zone development north of the North Arm (Hall, 2017b). Close to the end of the Late Miocene (Fig. 6A),volcaniclastics and gravity mass flow deposits of the Dolokapa Formation were deposited at the base of a marine slope near an unstable shelf edge in the Tilamuta Basin of eastern Gorontalo Bay suggesting significant uplift due to magmatism in the North Arm provided debris to the offshore basin (Rudyawan, 2016). In contrast, there is little indication of significant input of volcanic or clastic debris into Tomini Basin in western Gorontalo Bay and carbonates were continuously deposited during this period (Pholbud et al., 2012; Pezzati, 2016). On land SW of Gorontalo Bay there are volcaniclastic

turbidites containing shards and crystals from explosive terrestrial eruptions interpreted to be further SW. This suggests most volcanic debris from the SW was probably trapped in Poso Basin in the southern part of western Gorontalo Bay. Carbonate deposition was widespread in the area including the Tomini Basin and Togian Islands as far as the southern East Arm. There was minor uplift in the western East Arm that supplied ophiolitic-rich sediments to a coastal fan delta now forming the Bongka Formation in the northern part of Central Sulawesi, the East Arm and the Togian Islands. The exact age of the Bongka Formation is uncertain since it is inferred from foraminifera in reworked Pliocene limestone clasts and its stratigraphic position below the Pliocene Poso Formation. The distinctive ultramafic-rich sediments can only have been sourced in the East Arm. In northern West Sulawesi, volcaniclastics of the Tambarana Formation were deposited in a coastal fan setting. They were reworked from magmatic rocks in West Sulawesi (Bergman et al., 1996; Bellier et al., 1998; Hennig et al., 2015).

The Larona Formation in southeastern Central Sulawesi was deposited in an alluvial fan setting close to an ultrabasic source, probably in the latest Miocene based on Simandjuntak (1986); no samples suitable for biostratigraphic dating were found during this study. In South Sulawesi, uplifted land is inferred from volcanic breccias, lavas and tuffs of the Lemo Volcanics that yield K-Ar ages of 6.2 Ma (van Leeuwen, 1981). In the SE Arm, the uppermost part of the Pandua Formation records an increasing metamorphic component. The sediments are particularly distinctive since they contain blue glaucophane with lawsonite and chloritoid typical of high pressure-low temperature (HP-LT) metamorphic rocks such as those in nearby exhumed metamorphic complexes (e.g. in the Mendoke, Mekongga and Rumbia Mountains; de Roever, 1950, 1956; Helmers et al., 1989). Further SE, the uppermost part of the Tondo Formation of Buton received minor volcanic input. The few latest Miocene zircons (ca. 6-7 Ma), potassium and plagioclase feldspars are thought to have been derived locally from magmatism along strike-slip faults in the SE Arm or possibly from explosive eruptions in South Sulawesi. There was a significant sedimentation change in the SE Arm and Bone Bay, and possibly Tolo Bay, where the quartz-rich Langkowala Formation (including Unit D of Camplin and Hall, 2014) was deposited unconformably over the serpentinite-rich Pandua Formation in a shelf to delta slope environment. In Buton Island, the upper part of the Tondo Formation was deposited in a relatively deep marine environment and records coarsening-up and deepening-up successions (Wiryosujono and Hainim, 1975; Fortuin et al., 1990).

6.6. 5 Ma map

From 5 Ma onwards extension in North, Central and East Sulawesi was driven principally by the developing subduction of the Celebes Sea north of the North Arm. The continued extension in South and SE Sulawesi was driven mainly by Banda subduction rollback which has continued until the present-day.

Early Pliocene (Fig. 6B) magmatic products were deposited locally in the North Arm and extensively further south. In the Tilamuta Basin, Togian Islands and Poh Head (Rusmana et al., 1984; Simandjuntak, 1986; Cottam et al., 2011; Rudyawan, 2016) there are volcaniclastics deposited in a marine environment sourced mainly from the north. Rapid reworking of explosive volcanic products in a marine setting is indicated by water escape structures, slumps, and reworked foraminifera. Subsidence in Tomini Basin of northern Gorontalo Bay was marked by a change from gradational to retrogradational stacking patterns at the base of Pliocene Unit E of Pholbud et al. (2012). Possible equivalent carbonates were deposited in parts of the northern East Arm and in the Poso Basin of southern Gorontalo Bay (Unit 0 of Pezzati et al., 2014). Lower Pliocene coastal and alluvial plain deposits of the Bongka Formation in the Togian Islands interfinger with shallow marine carbonates. Provenance analyses indicate that ultrabasic, ophiolitic, metamorphic and older sedimentary rocks were sourced from the East Arm to the south. The distal equivalent of these sediments might have reached the Tilamuta Basin (Rudyawan, 2016). In the southern East Arm, basin subsidence is represented by the Kintom Formation which deepens up from an outer neritic to bathyal environment (Davies, 1990). Equivalent sediments were possibly deposited in Tolo Bay (redefined Unit C_2 of the Rudyawan and Hall, 2012).

In West Sulawesi, mudstones of the Lisu Formation were deposited in a shallow marine environment during the earliest Pliocene (Calvert, 2000; Calvert and Hall, 2007). The volcaniclastic Napu Formation may represent a terrestrial equivalent of the Lisu Formation further east, sourced by magmatism in West Sulawesi. In the Poso Depression of Central Sulawesi, ultramafic-rich conglomerates and sandstones at the base of the Puna Formation pass up into marine sediments deposited in a submarine fan and/or slope apron in a relatively deep-water environment (deeper than 200 m). Later, carbonates of the Poso Formation were deposited near the basin margin and siliciclastics of the Puna Formation in deeper water parts of an asymmetric basin. In the South Arm, the basal clastic Walanae Formation interfingers in places with reef talus of the Tacipi Formation. These sediments mark the onset of a rapid transgression that occurred at the same time as uplift and renewed volcanic activity to the west and northwest (van Leeuwen, 1981; Grainge and Davies, 1985). The upper part of the Tacipi Formation correlates to the south with the Selayar Limestone in Selayar Island.

In northern Bone Bay, Lower Pliocene conglomerates and sandstones of the Bulupulu Formation record significant input of volcanic and metamorphic detritus from West Sulawesi into the Bulupulu Sub-basin (Units D and E of Camplin and Hall, 2014) through a submarine channel. In the SE Arm, Pliocene carbonates of the Eemoiko Formation locally overlie thick laterites formed during earlier emergence of land and were deposited on a previously eroded shelf margin. Siliciclastics of the Pliocene Langkowala Formation were contemporaneously deposited in terrestrial and marginal marine settings (e.g. shoreface and delta front). Provenance studies indicate sources for these sediments were

the Triassic-Jurassic Meluhu Formation, HP-LT metamorphic rocks, and the reworked Pandua Formation. This suggests newly emergent highlands of metamorphic and Triassic-Jurassic sedimentary rocks blocked transport of ultramafic-rich sediment from the north. In Buton Island, basal pinnacle reefs are overlain by the deep-water (middle to bathyal) marls of the Sampolakosa Formation indicating significant basin deepening during the Pliocene (Wiryosujono and Hainim, 1975; Fortuin et al., 1990; Davidson, 1991).

6.7. 4 Ma map

The Tilamuta Basin (Fig. 1) of eastern Gorontalo Bay (Fig. 7A) still received volcaniclastic material from igneous centres of the North Arm (Rusmana et al., 1984; Simandjuntak, 1986; Cottam et al., 2011; Rudyawan, 2016). Pinnacle reefs in the northern parts of the Tilamuta Basin suggest rapid subsidence of the basin margin (Rudyawan, 2016). Backstepping carbonates in Tomini Basin of western Gorontalo Bay (Unit E of Pholbud et al., 2012) represent continued gradual, but intermittently rapid, subsidence.

In southwestern Sulawesi, tuffaceous sandstones and siltstones of the Mapi Formation were deposited in deep-water environments and were probably sourced from magmatic activity in West Sulawesi. The fining-up successions of the Puna Formation indicate continued subsidence and deepening in Central Sulawesi. Provenance analyses show that sediments were sourced mainly from the ultrabasic rocks in East Sulawesi with intermittent magmatic input from West Sulawesi. A fining-up sequence from conglomerate to sandstones and claystones in well BBA-1X (Sudarmono, 2000) indicates basin deepening in northern Bone Bay. Backstepping carbonates (Unit C of Camplin and Hall, 2014) in western Bone Bay and younger landward carbonates of the Eemoiko Formation in the SE Arm suggest continuous subsidence and widening of the basin towards SE Sulawesi. Equivalent subsidence-related retrogradational stacking patterns were also observed in Tolo Bay. The Sampolakosa Formation in Buton Island has an age of about 4 Ma (Fortuin et al., 1990). Reworked reefal deposits at the upper part of the Sampolakosa Formation were possibly sourced from uplifted parts of Buton Island (Fortuin et al., 1990).

6.8. 3 Ma map

Increasing areas of emergent land in the North Arm (Fig. 7B) are inferred from the clastic deposits of the Buol Beds and Lokodidi Formation (Advokaat, 2015; Rudyawan, 2016). The pinnacle reefs at the top of backstepping carbonates (Unit E of Pholbud et al., 2012) in Tomini Basin (Fig. 1) of western Gorontalo Bay indicate the beginning of a phase of rapid deepening of this basin. In the Tilamuta Basin, north-directed mass transport complexes, south-directed and east-directed prograding clinoforms in clastic sediments (Unit E of Rudyawan, 2016) suggest uplifted sources in the East Arm and North Arm. Widespread clastic deposits of the Bongka Formation in the northern and southern East Arm suggest significant uplift of the East Arm. Provenance analyses show a predominantly

ultrabasic source with subsidiary ophiolitic, volcanic and older sedimentary rocks. In the northern East Arm, sediments were deposited mainly in a submarine deltaic environment and buried the Lower Miocene carbonates. There was clastic deposition in eastern Poso Basin where pinnacle reefs are overlain by thick clastic strata (Pezzati et al., 2014). Deepening in this area suggests initiation of the Walea Strait that now separates the Togian Islands from the East Arm. Offshore of the southern East Arm, the Tolo-1 well penetrated deepening-up (from littoral to neritic setting) and subsequent shallowing-up sequences that consist of ultrabasic-rich sandstones, conglomerates and siltstones (Davies, 1990). Coeval successions recorded in the onshore southern East Arm include fluviatile clastics that are overlain by shallow marine carbonates and subsequent very thick coastal to alluvial fan ultrabasic-rich clastics indicating a short period of low clastic input and slight deepening followed by uplift. Prograding sequences (redefined Unit C_3 of Rudyawan and Hall, 2012) in Tolo Bay possibly correlate with the Upper Pliocene Bongka Formation in the southern East Arm which consists of ultrabasic-rich clastics that were sourced from uplifted areas in eastern Sulawesi.

Rapid uplift of land in West Sulawesi and increased elevation are suggested by rapid exhumation that is recorded by U-Pb, Ar-Ar and U/Th-He ages of igneous and metamorphic rocks (Hennig et al., 2015). These rocks were exhumed in West Central Sulawesi and were then eroded to produce material that was deposited in adjacent basins (Sukamto, 1973; Ratman, 1976; Sukamto and Simandjuntak 1983; Simandjuntak et al., 1991; Ratman and Atmawinata, 1993; Sukido et al., 1993; Simandjuntak et al., 1997; van Leeuwen and Muhardjo, 2005; Calvert and Hall, 2007; Hennig et al., 2015). There was a change to extensive coarse alluvial fan deposits of the Pasangkayu Formation (Calvert, 2000; Calvert and Hall, 2007). By this time, a land bridge is interpreted in southern Central Sulawesi following significant uplift in West and East Sulawesi connecting the two parts of the island. This is supported by the northwest-directed foresets seen on seismic lines over the top of carbonates of Tacipi Formation in the East Sengkang Basin (Grainge and Davies, 1985). In SE Sulawesi, there was increasing uplift on land and subsidence of offshore basins. On land metamorphic and Triassic-Jurassic sedimentary rocks were exhumed and became the main sources for the Langkowala Formation. Offshore, there are pinnacle reefs on top of backstepping carbonates (Eemoiko Formation equivalent) that are onlapped and downlapped by the extensive siliciclastics (Langkowala Formation equivalents, Fig. 2; Camplin and Hall, 2014). Channel aggradation within the clastic sequences suggests major clastic input from surrounding highlands.

6.9. 2 Ma map

By the Early Pleistocene (Fig. 8A), there had been significant recent palaeogeographic change across Sulawesi that included rise of high mountains and very rapid subsidence in offshore basins and Sulawesi was beginning to resemble its present form. By this time much of the North Arm was emergent. Sediments of the Lokodidi and Randangan Formations were deposited in tidal and probable

shallow marine environments, relatively close to land with nearby sources of volcanic, granitoid, limestone and coral debris (Advokaat, 2015; Rudyawan, 2016). On the western side of the Neck, the Palu Formation was deposited in an alluvial fan to fluviatile setting during the past 2 Myr. The oldest sediments are alluvial fan boulder conglomerate debris flows that rest directly on granites and metamorphic rocks that yield U-Pb, Ar-Ar and U/Th-He ages of 3.5 to 2.5 Ma (Hennig, 2015; Hennig et al., 2016, 2017). These basal successions pass up-section into finer grained fluviatile deposits. A conglomerate bed in the middle of the Palu Formation in the Neck contains unusual garnet peridotite, ophiolite and mylonitic boulders that are identical to boulders now common in the Bongka River of the East Arm except that the garnet peridotite boulders of the Palu Formation are altered to laterite. Despite the close similarity there is no direct pathway from the East Arm to the Neck. However, present-day drainage patterns suggest a complex Plio-Pleistocene history including several river captures and drainage reversals which could have provided indirect routes. For example, clasts could have been eroded from the East Arm during the Pliocene, deposited in northern West Sulawesi and later recycled into Pleistocene deposits. Garnet peridotites reported in the Palu-Koro fault valley (Tjia and Zakaria, 1974; Helmers et al., 1990; Kadarusman and Parkinson, 2000) could be a source but they have a very different appearance with much smaller garnets and a generally finer gained character. They also lack any association with distinctive ophiolite boulders typical of the Bongka River and Palu Formation.

In the Tilamuta Basin of eastern Gorontalo Bay, Lower Pleistocene sediments (Unit F of Rudyawan, 2016) were deposited in a deep marine environment and suggest sources to the north (volcanic rocks of the North Arm) and south (possible volcanic sources in the Togian Islands). In western Gorontalo Bay, deeply subsided pinnacle reefs are onlapped by clastic sediments (Unit F of Pholbud et al., 2012) that are possible correlatives of the Lokodidi and Palu Formations suggesting a source in the western North Arm or the Neck. Some pinnacle reefs have no clastic sediment cover suggesting growth as late as the Pleistocene in NW Tomini Basin and on the Lalanga Ridge. Significant uplift of the East Arm shed clastic sediments to the north and south. In the northern East Arm, the poorly consolidated upper Bongka Formation was deposited in an alluvial fan (now on land) to submarine fan setting (Unit 5 of Pezzati et al., 2014) in the western Poso basin. Possible equivalent sediments were deposited in Tolo Bay (Unit C_4 of Rudyawan and Hall, 2012). In the southern East Arm, Quaternary fluviatile sediments unconformably overlie the Pliocene Bongka Formation. Coeval carbonates of the Luwuk Formation were deposited on a shallow marine shelf (Davies, 1990; Sumosusastro et al., 1989). There was uplifted land in Central Sulawesi due to exhumation of the Pompangeo Schist Complex (PSC). As the marine area diminished there was deposition of the Lage Formation, on an unstable slope of an outer neritic shelf, which unconformably overlies Pliocene sediments. Heavy minerals include those sourced from the PSC. The equivalent fluviatile and floodplain deposits of the Tomata Formation deposited in southeastern Central Sulawesi include quartz

and metamorphic rock clasts that were also probably sourced from the PSC. In western Sulawesi, the Pasangkayu Formation includes alluvial fan deposits, sourced in nearby mountains to the east, that interfinger with marine deposits of a narrow shelf (Calvert and Hall, 2007).

Volcanic activity suggests that most of the southern South Arm was emergent by the Pleistocene (Sukamto, 1990; Bergman et al., 1996; Polvé et al., 1997; Elburg and Foden, 1999) although the northern part of the South Arm was still a shallow marine area (van den Bergh et al., 2016) around the Tempe Depression. In Bone Bay, the upper part of Unit E of Camplin and Hall (2014) includes Quaternary sediments that were deposited on slopes and in submarine channel-fan systems. Several drowned pinnacle reefs on structural highs suggest subsidence in the sub-basins continued to the present day (Camplin and Hall, 2014). In the SE Arm, the Langkowala Formation deposition lasted until about the Early Pleistocene (1.8-1 Ma) based on foraminifera analysis from field samples and the Abuki-1 well (Robertson Indonesia, 1989) and sediments were deposited at depths greater than ca. 200 m. These suggest that subsidence in the southern SE Arm continued until the Early Pleistocene. In Buton Island, carbonates of the Wapulaka Formation unconformably overlie the Sampolakosa Formation and were deposited in shallow water, inner neritic, reef or near reef environments (Fortuin et al. 1990; Davidson, 1991).

6.10. 1 Ma map

The palaeogeography of Sulawesi was by this time (Fig. 8B) very similar to the present (Fig. 9A). Significant and rapid increase in elevation formed high mountains up to 3 km. The inter-arm basins were close to their present depths of 1.5 to 2 km. The North Arm was largely emergent with lakes or barely connected inland seas near Gorontalo. It seems likely that these finally disappeared in the last few thousand years. There was a land connection between the North Arm and western Central Sulawesi as the Neck elevation increased. The abundant granitoid and diorite clasts in the upper part of the Palu Formation were derived from Neogene sources in western Central Sulawesi. The upper part of the Palu Formation also includes alluvial fan deposits that reworked older alluvial fans and limestones. These deposits are now tilted at up to 20° to the west, related to young uplift of the Neck. To the north of the Tokorondo Mountains in northeastern West Sulawesi are alluvial fan deposits that contain metamorphic, granitoid, ultrabasic and ophiolitic rocks reworked from older rocks in the Neck and west Central Sulawesi. Significant uplift on land was contemporaneous with very rapid subsidence in the inter-arm bays. In Gorontalo Bay, very young and continuous rapid subsidence is recorded by back-stepping pinnacle reefs now found at water depths between 1 and 2 km. By this time the Lalanga Ridge in the middle of Gorontalo Bay was probably submerged to close to its present depth; the tops of reef pinnacles are now at depths of 400-500 m (Pholbud et al., 2012).

In West Sulawesi, deep valleys incised steep mountains and expose deep crustal rocks intruded by young granites as the upper crust was stripped off (Hall, 2011; Hennig, 2015). The complex

drainage pattern suggests that up to this time sediments were transported northwards along the Palu River from the Tokorondo Mountains. Even younger uplift and river capture means that sediments are today carried west into the Makassar Strait and not to the north into Palu Bay, and the Palu River flows only from about 2°S south in the Palu-Koro fault valley. Thick sediments accumulated in the Poso Basin as far east as the Walea Strait but subsidence exceeded the sediment supply from the south so the basins deepened. In the northern East Arm, uplift is recorded by deposition of the Pleistocene Bongka Formation that contains reworked older siliciclastic rocks. There are some deep valleys incised into steep mountains which expose deep crustal rocks (e.g. Bongka River). In the southern East Arm, intermittent uplift is represented by several levels of Quaternary reef terraces of the Luwuk Formation along the coast that reach elevations of over 400 m above the sea level (Sumosusastro et al., 1989) where carbonates have ages of ca. 300 ka. These uplifted reefs correlate with submerged carbonates in the Peleng Strait, offshore southern East Arm (Davies, 1990) and just east of Poh Head (Ferdian et al., 2010) where former reefs are now at depths of ca. 1 km. The carbonates show the young and very complex localised patterns of uplift and subsidence within a broader regional picture of rapidly rising land and subsiding basins.

In central Sulawesi, metamorphic-rich coarse-grained deposits were deposited in alluvial fan and fluvial settings as deep crust continued to be exhumed in the Pompangeo and Tokorondo Mountains. In south Central Sulawesi, metamorphic and quartz-rich siliciclastics were also deposited in fluvial and alluvial fan settings and were probably sourced from exhumed metamorphic rocks in southeastern Central Sulawesi. There was a very shallow marine seaway that continued to separate the South Arm and West Sulawesi in the Tempe Depression which probably emerged very recently (less than 7 ka; Gremmen, 1990). Gradual uplift in South Sulawesi is indicated by a change from shallow marine to fluvio-lacustrine environments (van den Bergh et al., 2016). In SE Sulawesi, quartz-rich siliciclastics of the Allanga Formation were deposited in a fluvial setting inland and were also transported into adjacent basins of Bone Bay via submarine channels and fans (Unit E of Camplin and Hall, 2014). Differential uplift in SE Sulawesi and Buton Island is recorded by uplifted Quaternary limestone terraces at the southwestern end of the SE Arm, Muna Island, south Buton Island, and in the Wakatobi Islands (Fortuin et al., 1990, Davidson, 1991; Satyana and Purwaningsih, 2011).

7. Effects of changing sea level during the last 1 Myr

Although tectonically-induced changes in topography and bathymetry have been geologically very fast they are relatively slow compared to young glacially-induced changes in sea level. Hence, we use the present-day map as a guide to assess the effects of Quaternary changes in sea level, particularly during intervals of a few thousand to tens of thousands of years when there were significant changes in volumes of ice caps. Figure 9A shows a present-day map classified into the same bathymetric and topographic intervals used for the palaeogeographic maps, with marine abyssal, bathyal and shelf

categories; and terrestrial coast to lowland, highland, and very high mountain terrains. The map is based on global seafloor bathymetry derived from satellite observations and ship depth soundings (Smith and Sandwell, 1997; Becker et al., 2009; Sandwell et al., 2014) which is regularly updated (http://topex.ucsd.edu/marine_topo/), integrated in this study with detailed multibeam bathymetric data obtained in the Sulawesi region during hydrocarbon exploration (Orange et al., 2010) and information from publicly available British Admiralty nautical charts. Topography on land is from the NASA Shuttle Radar Topographic Mission (SRTM) processed by the Consortium for Spatial Information, CSI-CGIAR (http://srtm.csi.cgiar.org/). The grid cell size for the global bathymetry is approximately 1x1 km. The combination of cell size and problems with interpreting satellite data in shallow marine areas means that bathymetric mapping close to coastlines is the least accurate. For the Sulawesi region this is largely overcome by the integration of multibeam data with a grid of 25x25 m cells and reference to nautical charts, but there are small areas close to coasts where there may be shallow ridges or deep channels which are not identified. For biogeographers these could be significant.

Possible glacially-induced changes in the last 1 Myr are illustrated by two maps (Fig. 9B and Fig. 9C), simply by changing sea level. Figure 9B shows the palaeogeography after lowering sea level by 150 m – an amount greater than sea level change of 120-130 m inferred for Last Glacial Maximum (LGM) at about 20 ka (Lambeck et al., 2002) and similar to that suggested during other intervals of lower sea level in the last 450 kyr (Siddall et al., 2003); errors on these estimates suggest the change could have been up to 150 m (Clark et al., 2009). In general, there is little effect on the island's shape, except for a widening of coastal areas around the South and SE Arms. Islands south of the SE Arm (Kabaena, Muna, Buton, Wowoni) become connected to the rest of Sulawesi, but the Togian Islands, Una-Una volcano, the Banggai-Sula Islands, Selayar and the Tukang Besi Islands remain separated, albeit by narrow, but relatively deep, straits.

Figure 9C shows the palaeogeography after raising sea level by 50 m, a change likely only if there was almost complete melting of the polar ice caps, but a value chosen to illustrate an extreme. Miller et al. (2005) estimated that sea level was 50 to 70 m higher than today in the Late Cretaceous (ca. 80 Ma) and 70 to 100 m higher from 60 to 50 Ma in an ice-free world, but sea level in the past 1 million years has probably been only a few metres above present values (Overpeck et al., 2009). Again, there is little effect on the present-day shape of the island, largely reflecting common steep coastlines and narrow steep marine shelves. All the present-day islands not part of the main island remain islands, albeit with smaller areas. The most notable change is the isolation of the South Arm from the rest of Sulawesi by the Tempe Depression. All the inter-arm bays remain submerged.

8. Conclusions

Neogene changes in palaeogeography in Sulawesi occurred after tectonic assembly of the Sulawesi region following a collision between an Australian continental promontory, the Sula Spur,

with the North Sulawesi volcanic arc. Mountains formed at this time and there was onset of widespread deposition of ultrabasic-rich sediments in eastern Sulawesi.

Sulawesi was initially a group of separated islands in western and eastern Sulawesi that were separated mainly by shallow water from the Early to Middle Miocene. Landscape change and basin development after the collision was greatly influenced by extension-related uplift and subsidence. Significant change of basin width in the Late Miocene separated the South Arm and the SE Arm, and western and eastern Central Sulawesi.

Most of the present relief of Sulawesi was created in the last 5 Myr, and especially since 2 Ma, reflecting significant tectonic change in a geologically short time. The Early Pliocene was a critical time; major uplift began, driven by extension, beginning major clastic input to the offshore basins, accompanied by significant subsidence of the inter-arm basins in Gorontalo Bay and Bone Bay. Land areas began to increase in size and become higher from the mid Pliocene but they remained separated by shallow water. A land bridge between eastern and western Sulawesi possibly formed in the Late Pliocene contemporaneously with rapid subsidence in the inter-arm basins. The land connections between Sulawesi's arms formed in the Late Pleistocene, except for the South Arm that remained separated by a shallow seaway.

A landscape similar to the present-day, with similar relief (mountains up to 3 km high separated by inter-arm basins with water depths of 1.5 to 2 km), developed from ca. 2 Ma. Glacial sea level change could have intermittently isolated or connected some islands, such as those in the Buton Group, but most of the smaller islands around Sulawesi would have remained separated by deep, albeit narrow, channels which could have been significant biogeographic barriers if currents were focused and strong. The Tempe Depression was probably the most significant wider barrier during intervals of higher sea level because it is so close to sea level at present. Flooding of this area would have isolated most of the South Arm from the main Sulawesi Island.

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Figure Captions

Fig. 1. Principal geographic and geological locations in and around Sulawesi referred to in the text. Red dots are named wells drilled during exploration for hydrocarbons. Green text with FZ are major fault zones crossing parts of the island, most of which are active and have significant geomorphological expression.

Fig. 2. Compilation of Neogene stratigraphy for different areas of Sulawesi. Information is from new work by Nugraha (2016) integrated with previous studies by van Leeuwen (1981), Sukamto and Supriatna (1982), Grainge and Davies (1985), Simandjuntak (1986), Davies (1990), Fortuin et al. (1990), Davidson (1991), Smith and Silver (1991), Simandjuntak et al. (1991, 1997), Rusmana et al. (1993), Calvert (2000), Sudarmono (2000), Wilson (2000), van Leeuwen and Muhardjo (2005), Hasanusi et al. (2004), Calvert and Hall (2007), Bromfield and Renema (2011), Cottam et al. (2011), Pholbud et al. (2012), Camplin and Hall (2014), Advokaat (2015), Hennig (2015), van den Bergh et al. (2016) and Rudyawan (2016). For Tolo Bay (1) is from Rudyawan and Hall (2012) and (2) is alternative proposed by Nugraha (2016).

Fig. 3. Simplified geological map of Sulawesi based on Sukamto (1973, 1982, 1990), Ratman (1976), Sukamto and Supriatna (1982), Rusmana et al. (1984), Simandjuntak et al. (1991, 1993a,b), Bachri et al. (1993), Ratman and Atmanwinata (1993), Rusmana et al. (1993), Sukido et al. (1993), Supandjono and Haryono (1993), Surono et al. (1993), Sukamto et al. (1994), Sikumbang and Sanyoto (1995), Apandi and Bachri (1997), Effendi and Bawono (1997), Simandjuntak and Surono (1997), Djuri et al. (1998) and Calvert (2000).

Fig. 4. A. Palaeogeography of Sulawesi at 20 Ma. Grey outline indicates reconstructed position of different parts of the present-day Sulawesi as a guide to location. Symbols on map are explained in upper left key: they show locations of dated sedimentary rocks with interpreted environment of deposition (circles and squares); different composition of igneous rocks (triangles); and Neogene metamorphic rocks (crosses). Colours represent different bathymetric and topographic intervals, classified into marine abyssal (below 4000m deep), bathyal (4000m to 200 m deep) and shelf (200m to sea level) categories; and terrestrial coast to lowland (sea level to 1000 m), highland (1000m to 2000m), and very high mountain (2000m and above) terrains. Sediment data points: 22; igneous data points: 12. B. Palaeogeography of Sulawesi at 15 Ma. Sediment data points: 31; igneous data points: 3.

Fig. 5. A. Palaeogeography of Sulawesi at 10 Ma. Sediment data points: 35; igneous data points: 17. B. Palaeogeography of Sulawesi at 8 Ma. Sediment data points: 106; igneous data points: 30. Symbols and colours are explained in caption to Figure 4.

Fig. 6. A. Palaeogeography of Sulawesi at 6 Ma. Sediment data points: 35; igneous data points: 17. B. Palaeogeography of Sulawesi at 5 Ma. Sediment data points: 139; igneous data points: 31; metamorphic data points: 4. Symbols and colours are explained in caption to Figure 4.

Fig. 7. A. Palaeogeography of Sulawesi at 4 Ma. Sediment data points: 159; igneous data points: 22; metamorphic data points: 8. B. Palaeogeography of Sulawesi at 3 Ma. Sediments data points: 125; igneous data points: 10; metamorphic data points: 2. Symbols and colours are explained in caption to Figure 4.

Fig. 8. A. Palaeogeography of Sulawesi at 2 Ma. Sediment data points: 106; igneous data points: 12. B. Palaeogeography of Sulawesi at 1 Ma. Sediment data points: 75; igneous data points: 4. Symbols and colours are explained in caption to Figure 4.

Fig. 9. A. Present-day geography of Sulawesi with same colour classification for different bathymetric and topographic intervals as that used on palaeogeographical maps. B. Palaeogeography after lowering sea level by 150 m using the present-day geography of Sulawesi shown in A. Most of the groups of small islands around the main island of Sulawesi remain separated by marine channels except for the Buton-Muna group south of the SE Arm. C. Palaeogeography after raising sea level by 50 m using the present-day geography of Sulawesi shown in A. The main island becomes slightly smaller, the South Arm is separated from the rest of Sulawesi by the Tempe Depression and the Buton-Muna group south of the SE Arm is also separated. Otherwise there is little effect on the shape of the island, or on the surrounding smaller islands which become a little smaller.

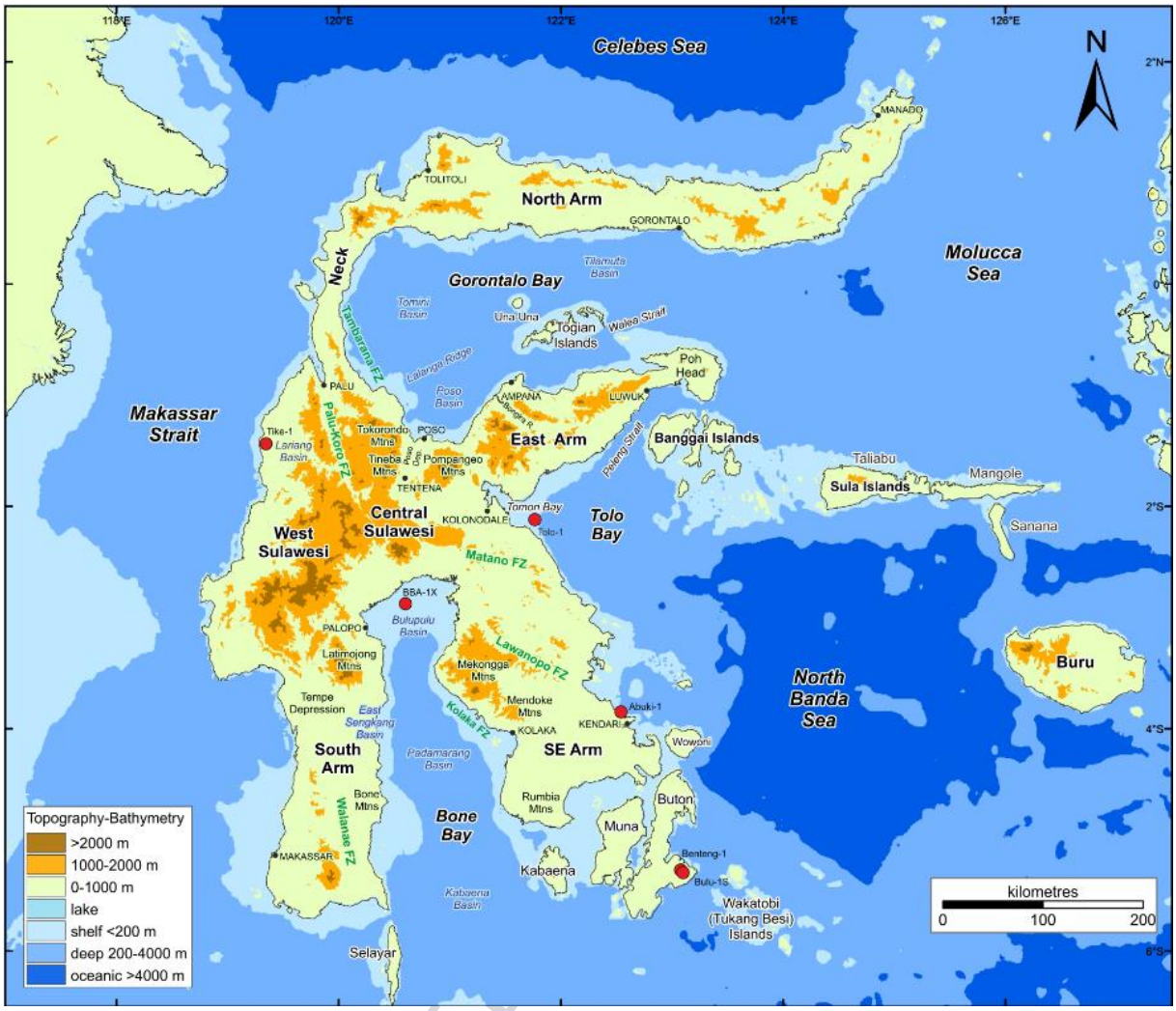


Figure 1

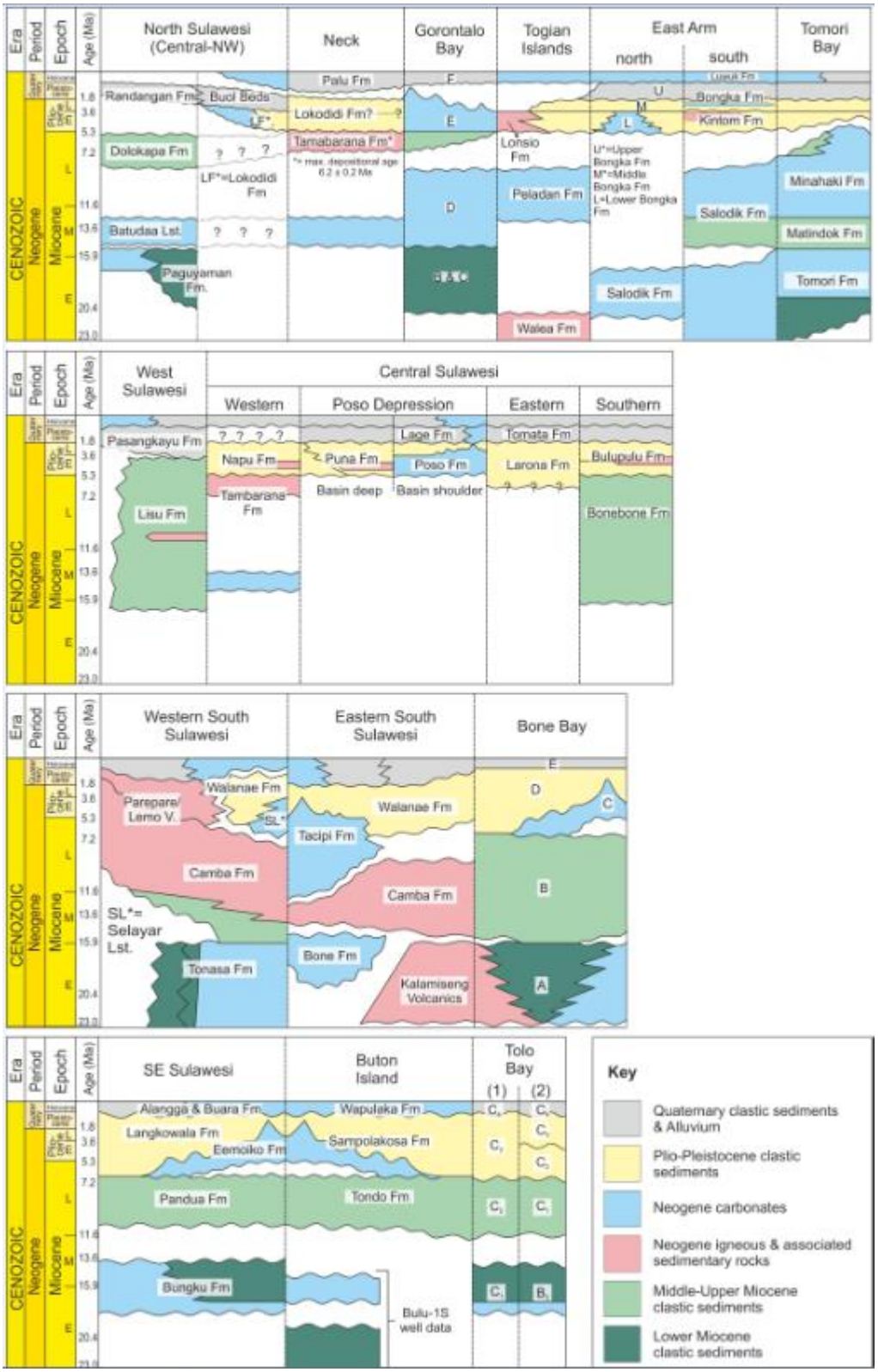

Era
Period
Epoch
Age (Ma)
CENOZOIC
Neogene
Miocene
North Sulawesi (Central-NW)
Neck
Gorontalo Bay
Togian Islands
East Arm
north
south
Tomori Bay
Palu Fm
Randangan Fm
Buol Beds
LF*
Lokodidi Fm?
Tamabarana Fm*
Dolokapa Fm
LF*=Lokodidi Fm
Batudaa Lst.
Paguyaman Fm.
Lonsio Fm
Peladan Fm
Walea Fm
Bongka Fm
Kintom Fm
Salodik Fm
Minahaki Fm
Matindok Fm
Tomori Fm
West Sulawesi
Central Sulawesi
Western
Poso Depression
Eastern
Southern
Pasangkayu Fm
Napu Fm
Tambarana Fm
Lisu Fm
Puna Fm
Lage Fm
Poso Fm
Basin deep
Basin shoulder
Tomata Fm
Larona Fm
Bulupulu Fm
Bonebone Fm
Western South Sulawesi
Eastern South Sulawesi
Bone Bay
Parepare/ Lemo V.
Walanae Fm
Tacipi Fm
Camba Fm
SL*= Selayar Lst.
Tonasa Fm
Bone Fm
Kalamiseng Volcanics
SE Sulawesi
Buton Island
Tolo Bay
(1)
(2)
Alangga & Buara Fm
Langkowala Fm
Eemoiko Fm
Pandua Fm
Bungku Fm
Wapulaka Fm
Sampolakosa Fm
Tondo Fm
Bulu-1S well data
Key
Quaternary clastic sediments & Alluvium
Plio-Pleistocene clastic sediments
Neogene carbonates
Neogene igneous & associated sedimentary rocks
Middle-Upper Miocene clastic sediments
Lower Miocene clastic sediments

Figure 2

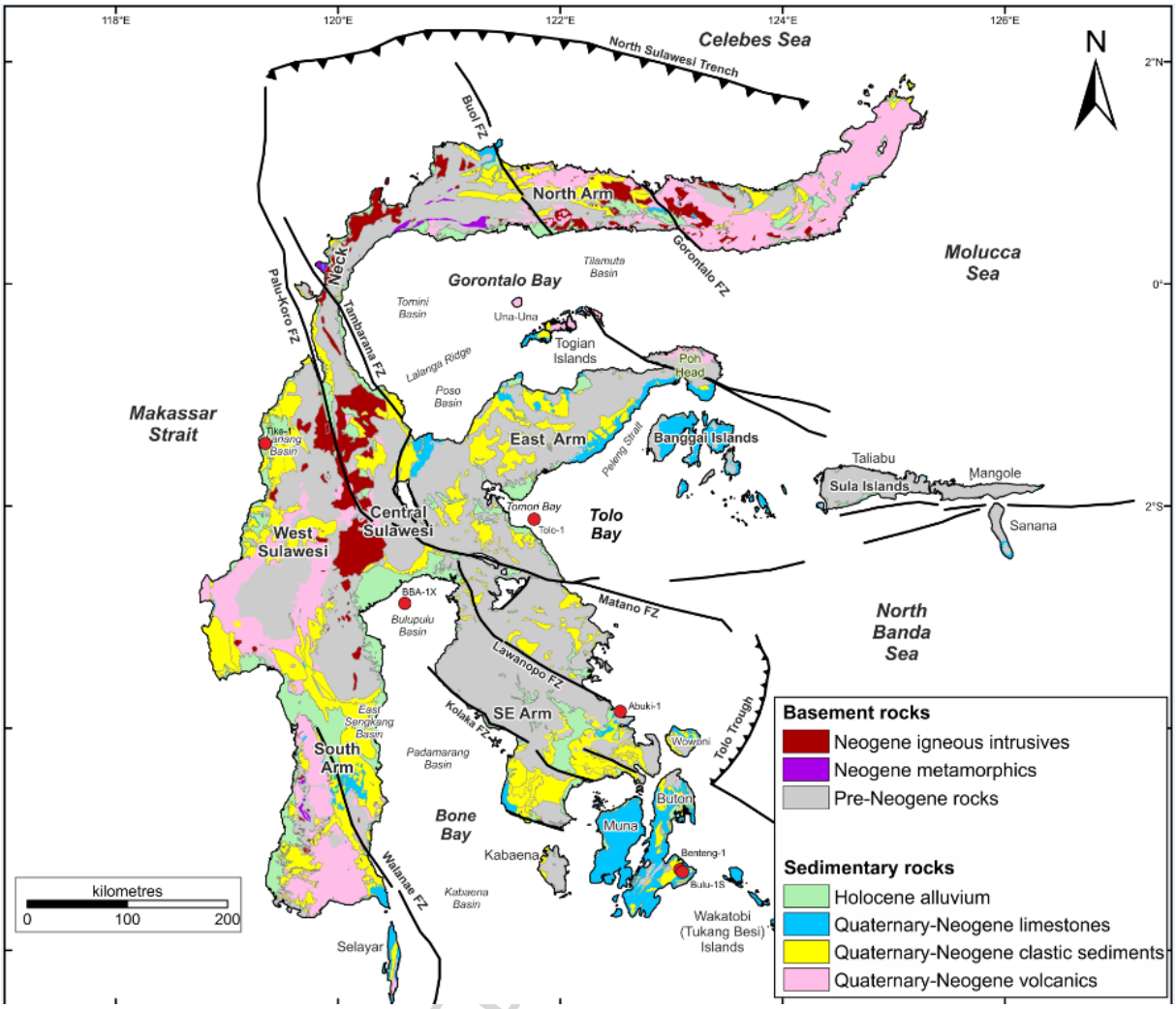


Figure 3

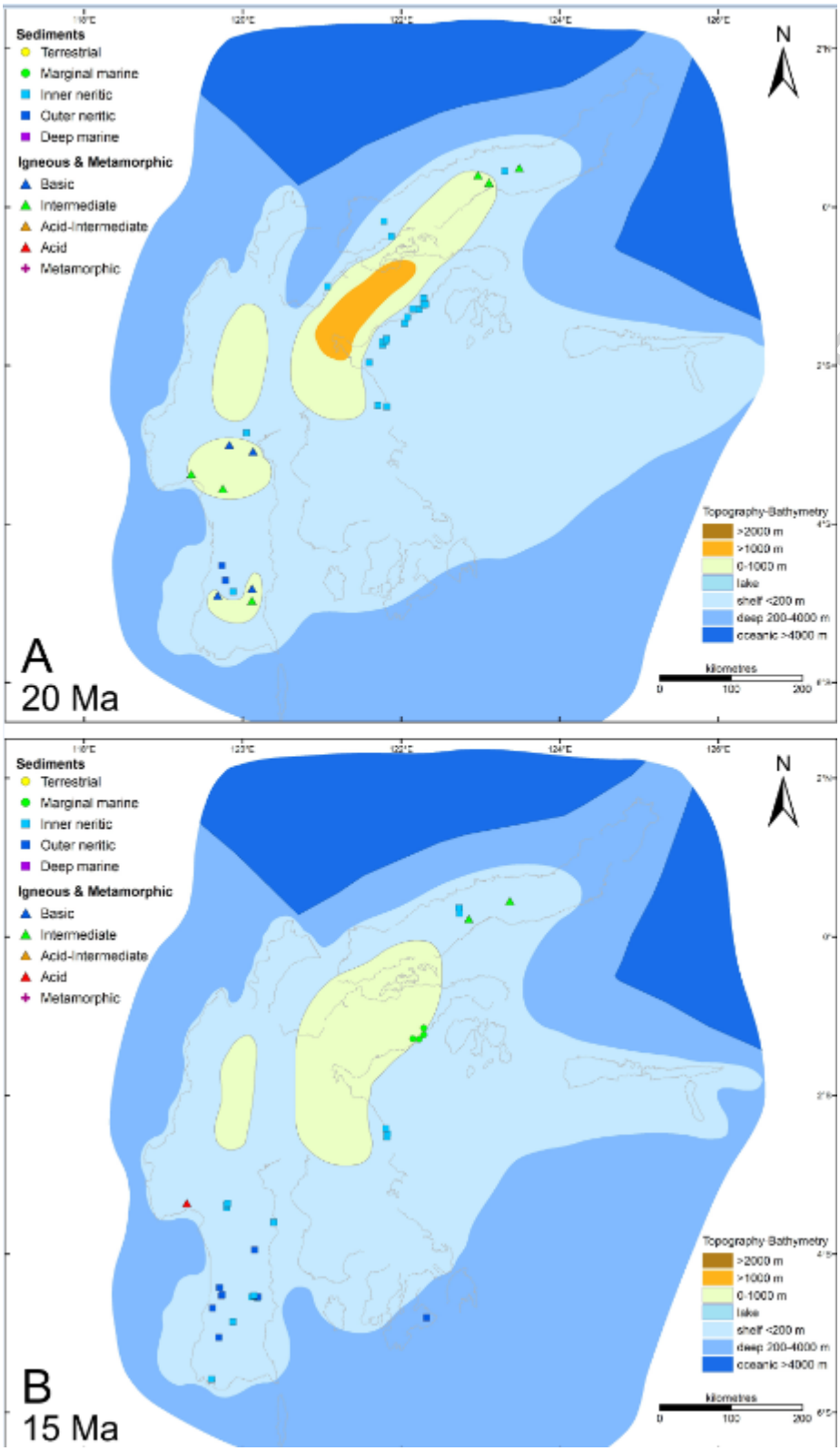

Sediments
Terrestrial
Marginal marine
Inner neritic
Outer neritic
Deep marine
Igneous & Metamorphic
Basic
Intermediate
Acid-Intermediate
Acid
Metamorphic
N
Topography-Bathymetry
>2000 m
>1000 m
0-1000 m
lake
shelf <200 m
deep 200-4000 m
oceanic >4000 m
kilometres
0
100
200
A
20 Ma
Sediments
Terrestrial
Marginal marine
Inner neritic
Outer neritic
Deep marine
Igneous & Metamorphic
Basic
Intermediate
Acid-Intermediate
Acid
Metamorphic
N
Topography-Bathymetry
>2000 m
>1000 m
0-1000 m
lake
shelf <200 m
deep 200-4000 m
oceanic >4000 m
kilometres
0
100
200
B
15 Ma

Figure 4

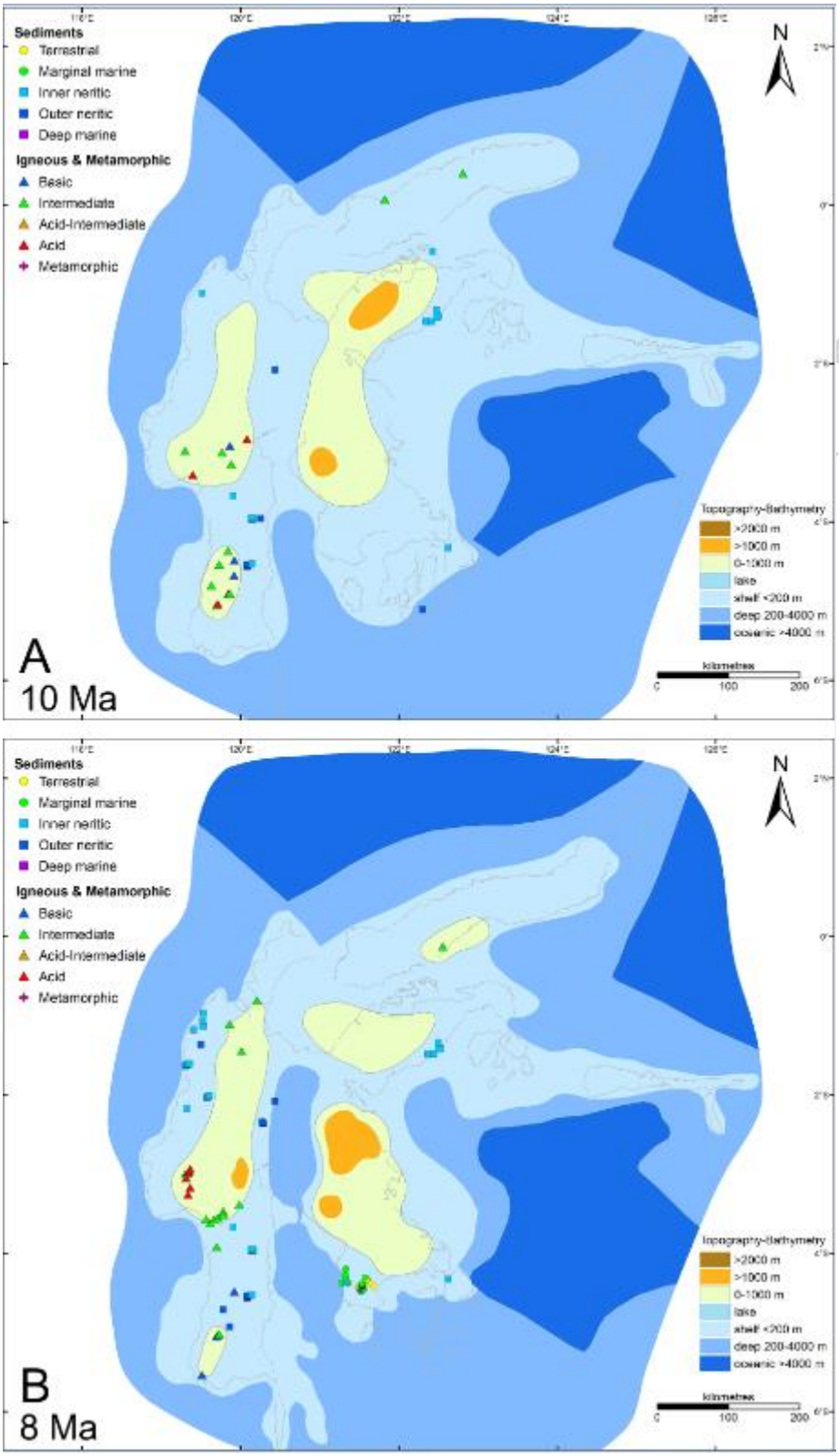
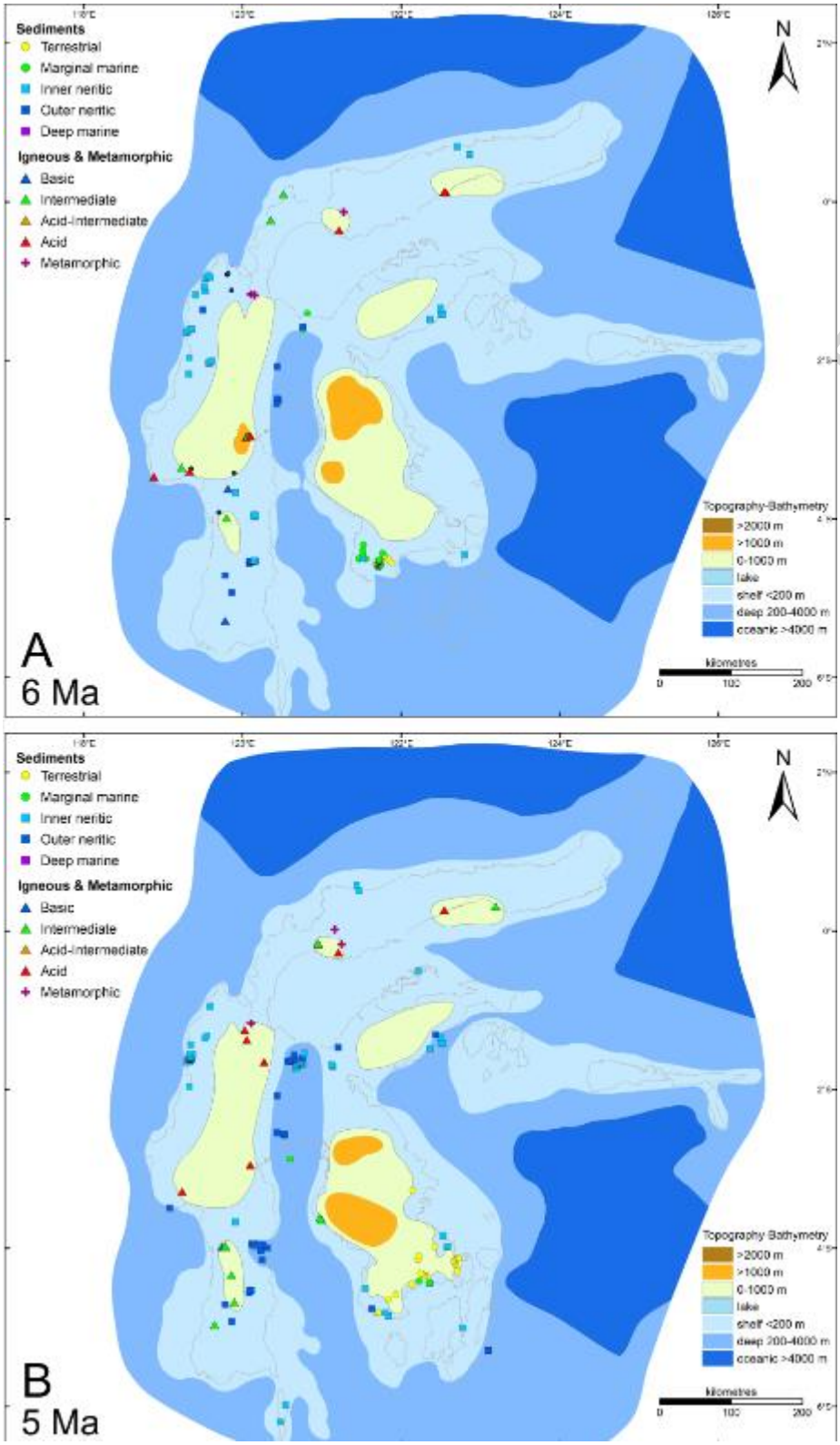

Sediments
Terrestrial
Marginal marine
Inner neritic
Outer neritic
Deep marine
Igneous & Metamorphic
Basic
Intermediate
Acid-Intermediate
Acid
Metamorphic
N
Topography-Bathymetry
>2000 m
>1000 m
0-1000 m
lake
shelf <200 m
deep 200-4000 m
oceanic >4000 m
kilometres
0
100
200
A
10 Ma
B
8 Ma

Figure 5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Marginal marine
Inner neritic
Outer neritic
Deep marine
Igneous & Metamorphic
Basic
Intermediate
Acid-Intermediate
Acid
Metamorphic
N
Topography-Bathymetry
>2000 m
>1000 m
0-1000 m
lake
shelf <200 m
deep 200-4000 m
oceanic >4000 m
Kilometres
0
100
200
A
6 Ma
Sediments
Terrestrial
Marginal marine
Inner neritic
Outer neritic
Deep marine
Igneous & Metamorphic
Basic
Intermediate
Acid-Intermediate
Acid
Metamorphic
N
Topography Bathymetry
>2000 m
>1000 m
0-1000 m
lake
shelf <200 m
deep 200-4000 m
oceanic >4000 m
Kilometres
0
100
200
B
5 Ma

Figure 6

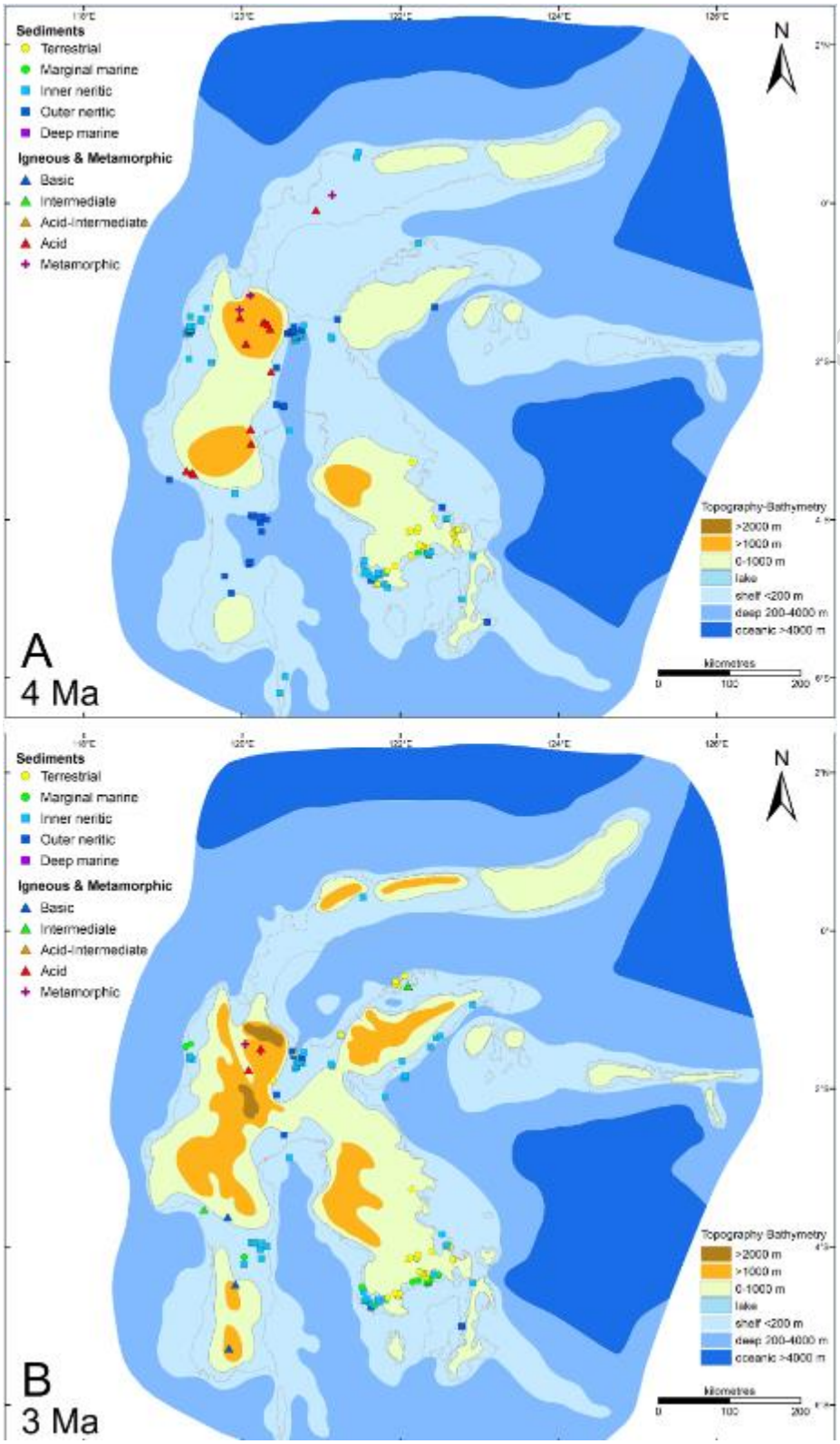
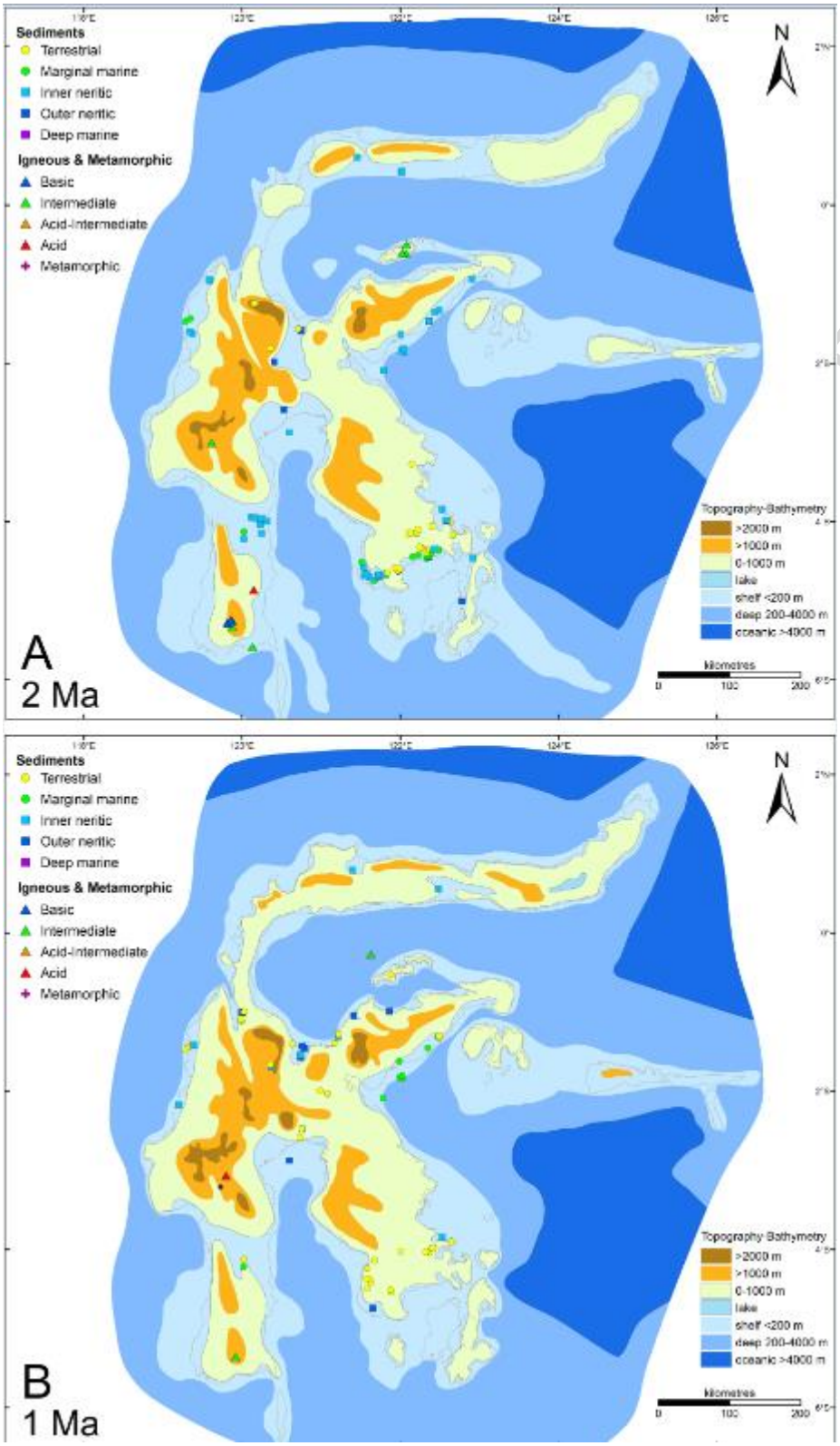

Sediments
Terrestrial
Marginal marine
Inner neritic
Outer neritic
Deep marine
Igneous & Metamorphic
Basic
Intermediate
Acid-Intermediate
Acid
Metamorphic
N
Topography-Bathymetry
>2000 m
>1000 m
0-1000 m
lake
shelf <200 m
deep 200-4000 m
oceanic >4000 m
kilometres
0
100
200
A
4 Ma
Sediments
Terrestrial
Marginal marine
Inner neritic
Outer neritic
Deep marine
Igneous & Metamorphic
Basic
Intermediate
Acid-Intermediate
Acid
Metamorphic
N
Topography-Bathymetry
>2000 m
>1000 m
0-1000 m
lake
shelf <200 m
deep 200-4000 m
oceanic >4000 m
kilometres
0
100
200
B
3 Ma

Figure 7


Sediments
Terrestrial
Marginal marine
Inner neritic
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Igneous & Metamorphic
Basic
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Acid-Intermediate
Acid
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N
Topography-Bathymetry
>2000 m
>1000 m
0-1000 m
lake
shelf <200 m
deep 200-4000 m
oceanic >4000 m
kilometres
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100
200
A
2 Ma
B
1 Ma

Figure 8

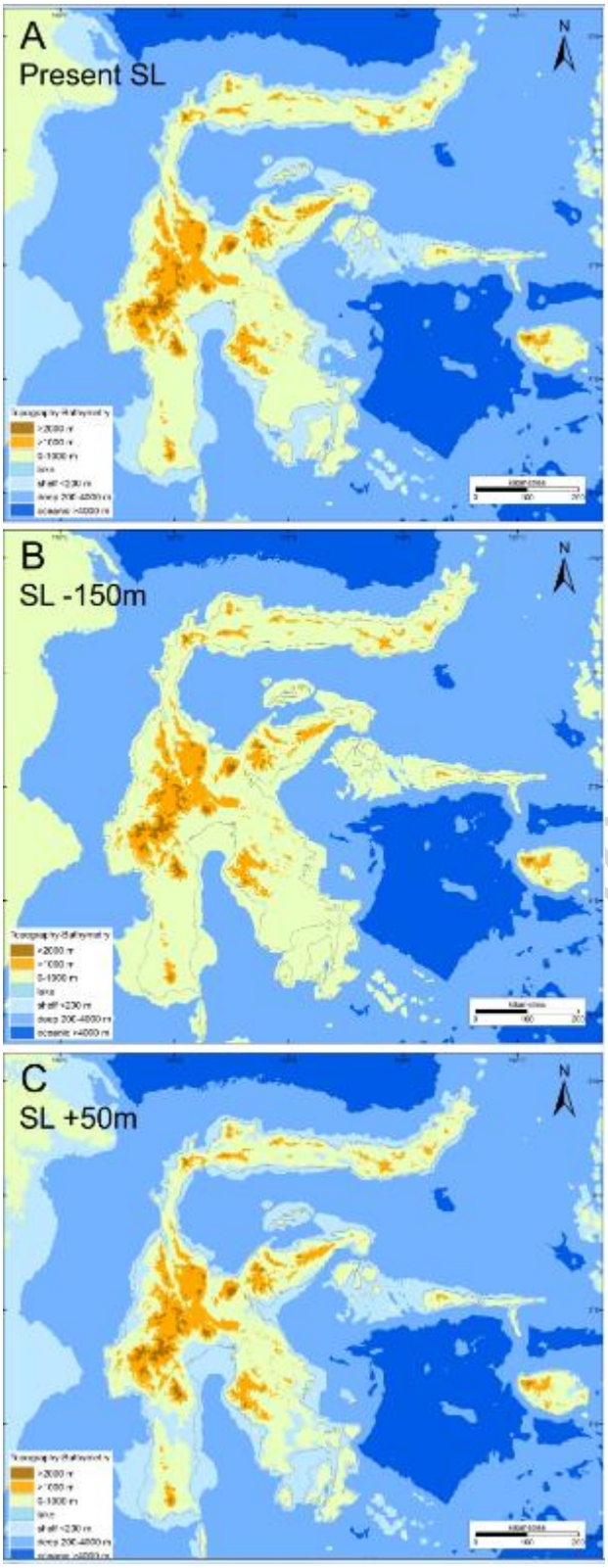
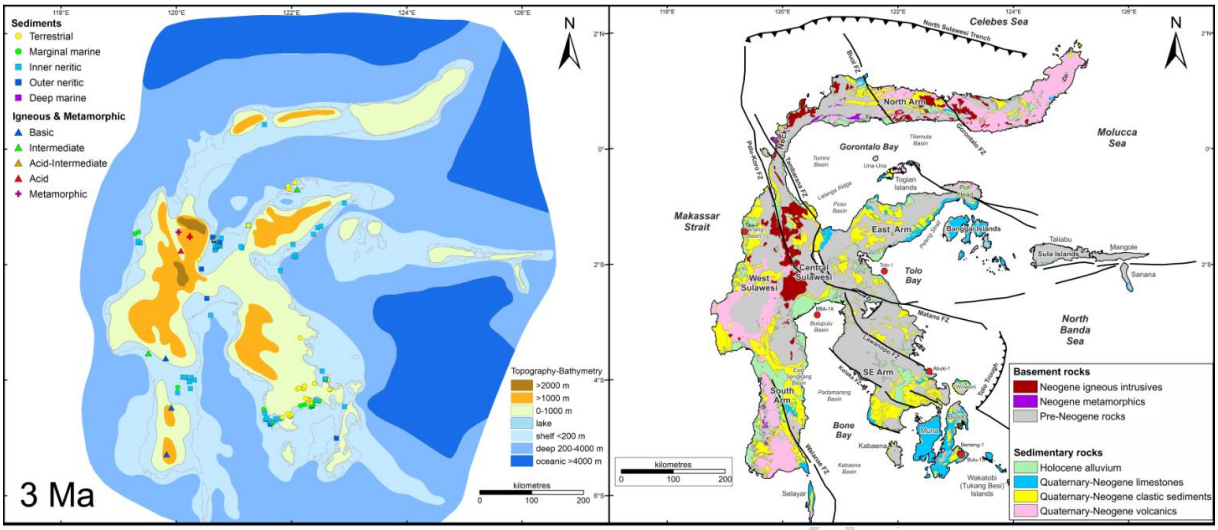


Figure 9



Graphical abstract

HIGHLIGHTS

New detailed Neogene palaeogeographic maps for Wallace's anomalous island

Modern biodiversity and endemism linked to Neogene geological change

Strange K-shaped Island at centre of Wallacea developed from many smaller islands

Modern landscape of high mountainous arms separated by deep inter-arm bays very young