Aspects of the geological development of the Makassar Strait, Indonesia

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ABSTRACT

The Makassar Strait is a Cenozoic extensional deep-water basin bounded to the east by Borneo and the Mahakam Delta system, to the west by Sulawesi, to the north by a zone of deformation associated with strike-slip movements and the North Sulawesi Fold-and-Thrust Belt, and to the south by the Paternoster Platform. It comprises a maximum of 7 km of Paleogene shallow- to non-marine synrift sedimentary rocks and volcanics, and Paleogene to Neogene post-rift deep-water sediments overlying a basement of attenuated continental crust with volcanics.

Early Miocene uplift of Borneo resulted in the deposition of large volumes of Neogene sediment in the Kutai Basin, some of which was remobilised from the Mahakam Delta and deposited in east-directed fan systems in the Makassar Strait. Pliocene tectonic events in west Sulawesi formed the West Sulawesi Fold Belt and west-directed turbidites in the central and eastern Makassar Strait. Current turbidite sedimentation in the central part of the strait is north directed through the Makassar Fan, and primarily sourced from the Lariang River in west Sulawesi.

Keywords: Indonesia, tectonics, deep-water sedimentation

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INTRODUCTION

The Makassar Strait (Fig. 1) between Borneo and Sulawesi (formerly Celebes) in eastern Indonesia is a north–south seaway approximately 600 km long and 100–200 km wide with water depths greater than 2,000 m. It is an important oceanic gateway allowing the main branch of the Indonesian Throughflow, which transports water from the Pacific into the Indian Ocean. It is the spiritual heartland of Wallacea—the series of islands stretching between the Eurasian and Australian continents—(Fig. 1 inset), as it was here that Alfred Russell Wallace first recognised the spectacular divide between Asian and Australo-Pacific biogeography, and established the 'Wallace Line' (Wallace 1863; Fig. 1).

Although numerous studies examined the onshore geology of Borneo and Sulawesi during the twentieth century, it was not until the advent of marine seismic acquisition and the discovery of major hydrocarbon deposits in the Mahakam Delta in the 1970s that any attention was given to the offshore geology of the Makassar Strait. This paper utilises petroleum industry seismic and high-resolution bathymetric data to illustrate aspects of the geological development of the Makassar Strait.

Geological setting and development

The formation of the Makassar Strait and nature of the underlying crust have long been the subject of scientific debate. One of the earliest observations was by Wallace in 1858:

> *In this Archipelago there are two distinct faunas rigidly circumscribed, which differ as much as those of South America and Africa, and more than those of Europe and North America: yet there is nothing on the map or on the face of the islands to mark their limits. The boundary line often passes between islands closer than others in the same group. I believe the western part to be a separated portion of continental Asia, the eastern the fragmentary prolongation of a former Pacific continent.* (Letter to Henry Bates 1858).

The Makassar Strait (Fig. 1) lies within a highly complex and dynamic plate tectonic setting where 3 major tectonic plates meet the oceanic/continental Indo–Australian Plate, the predominantly continental Eurasian Plate, and oceanic Pacific/Philippine Sea plates. Rapid geographic changes have occurred over the past 100 million years; biogeographic complexity reflects significant changes in the vertical and horizontal distribution of land and sea during the Neogene, which in turn reflects the complex geological history, largely driven by subduction and strike–slip fault movements (Hall 2011, 2012 and references therein). The region is extremely susceptible to seismic activity, primarily because the compressional tectonic boundaries are lined by volcanic arcs.

The Makassar Strait, within Sundaland (the south-eastern extension of the continental portion of Southeast Asia), is bounded to the west by the island of Borneo, to the east by Sulawesi, and to the north by a zone of tectonic disturbance which terminates in the North

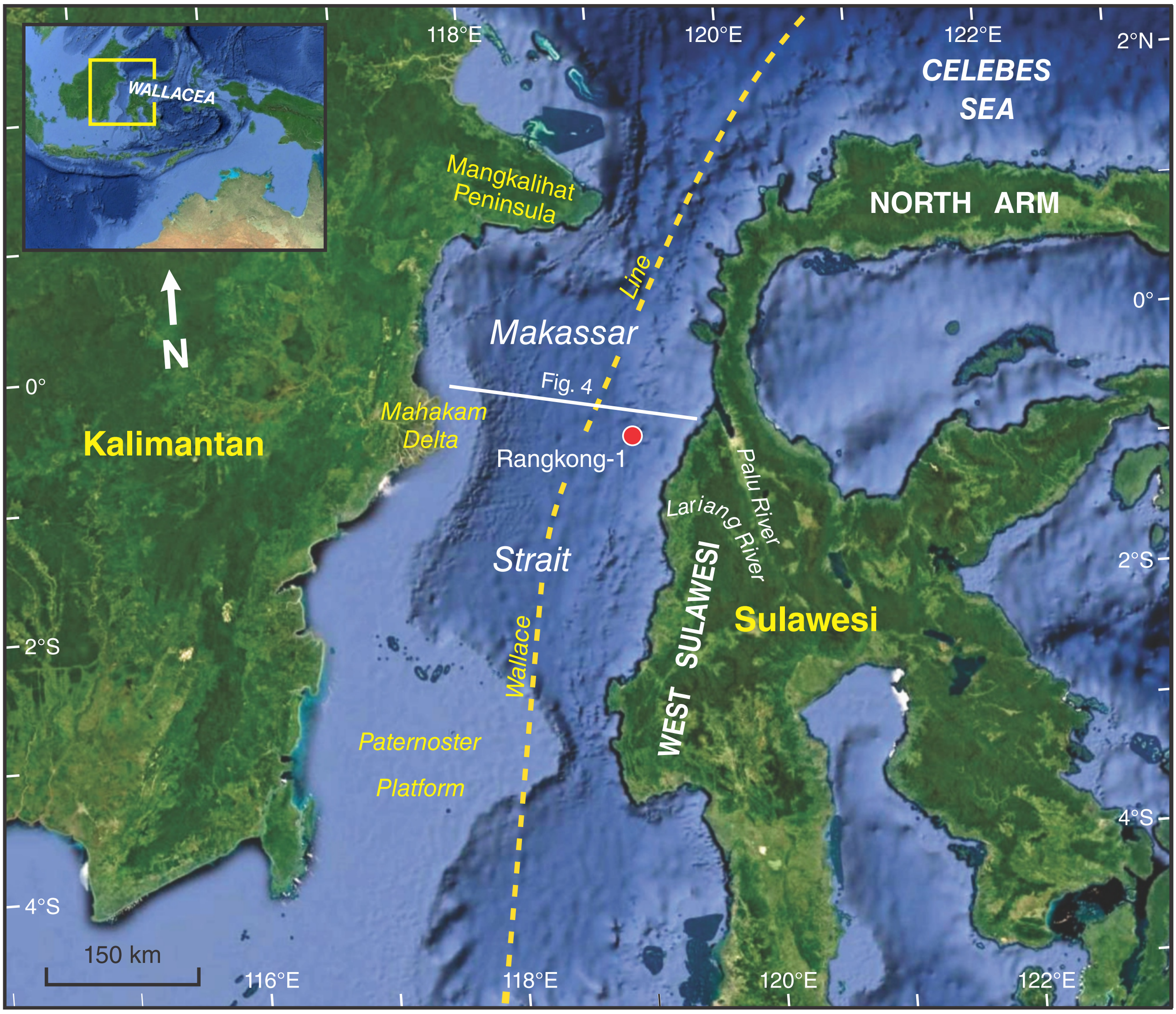

Figure 1. Locality map of Makassar Strait; inset shows regional position (Google Earth).

Sulawesi subduction system. To the south is the relatively stable Paternoster Platform, which is the northern boundary of the South Makassar Basin (Fig. 1). Water depths range from 0 to 2,500 m with gentle topography and broad shelves on the Borneo side of the basin and rugged terrain and a narrow shelf on the Sulawesi side. Five distinct morphotectonic units (geomorphic units having a distinct and common tectonic origin) are recognised (Fig. 2) and described below. Seismic images from various parts of the Makassar Strait are illustrated in Figure 3, and a geoseismic section from the Mahakam Delta to western Sulawesi is shown as Figure 4.

Hamilton (1979) interpreted the Makassar Strait as being underlain by oceanic crust, an interpretation supported by modelling of the gravity data (Cloke *et al*. 1999). Based on considerable anomalies in gravity and limited seismic data availability, other workers (e.g. Situmorang 1989) considered the basement to consist of extended continental crust that had been subjected to Paleogene rifting. Although Hall *et al*. (2009) considered the southern part of the strait to be underlain by extended continental crust, they also suggested the northern parts were likely to overlie middle Eocene oceanic crust with the junction between continental and oceanic crust beneath the Mahakam Delta.

Where it can be observed, the top of acoustic basement in the Makassar Strait is marked by a strong, distinctly hummocky, seismic reflector that possibly encompasses volcanic mounds or carbonate build-ups (Fig. 5a). These features locally display weak internal structuring and may have vertical relief of over one second TWT, although typically in the range of 200–300 milliseconds. During Cenozoic deformation, they acted as points of anisotropy, the focus for small-scale polygonal faults (see fault patterns above interpreted volcanoes, Fig. 5a). 3D seismic data from the central Makassar Strait clearly shows sedimentary packages within the basement succession, thus ruling out basement being oceanic crust. We interpret that the northern Makassar Strait is floored by thinned continental crust and that apparent conical structures are volcanic edifices analogous to those found in the Lake Kivu region of the Great African Rift (Fig. 5b).

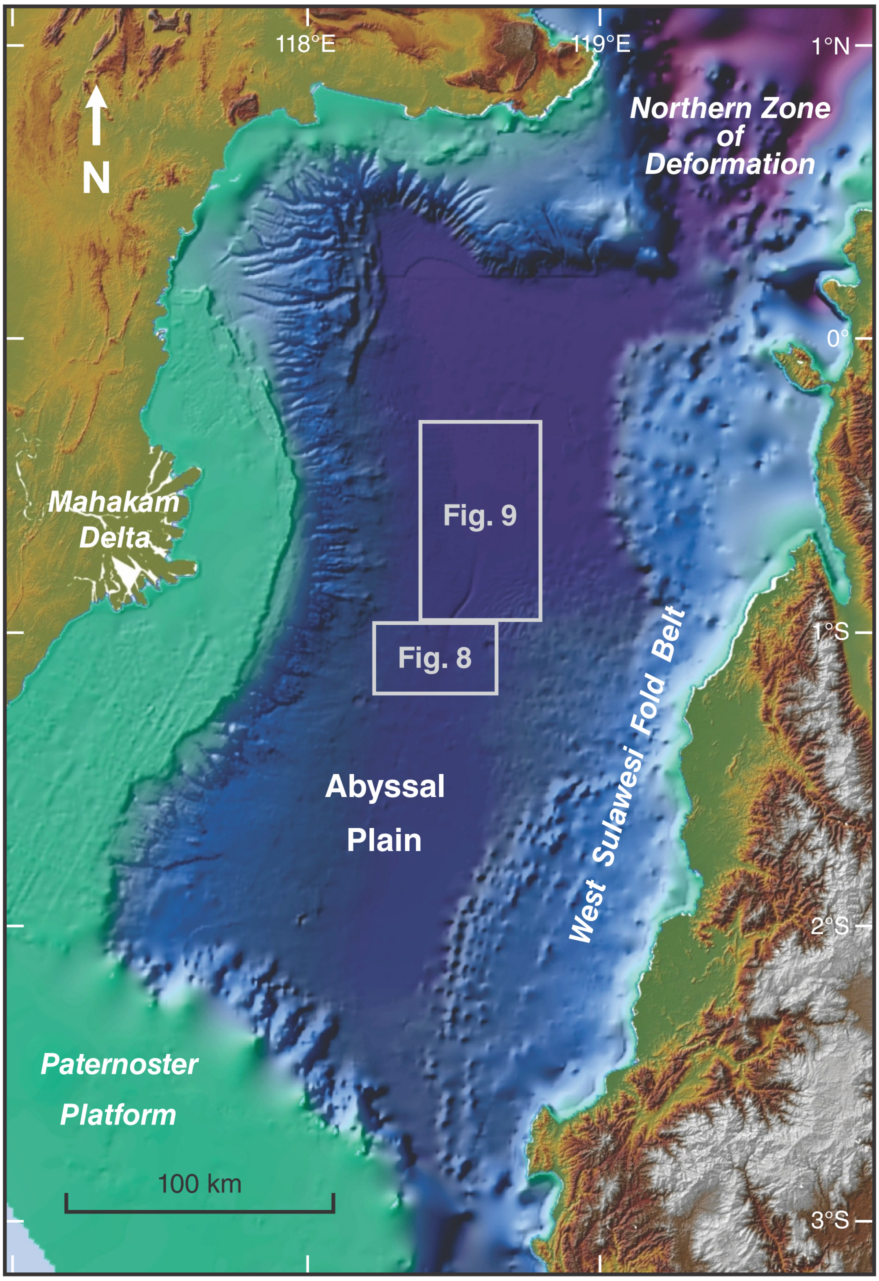

Figure 2. Makassar Strait bathymetric image (after Teas *et al*. 2004) with tectonomorphic areas indicated.

West of the Makassar Strait, Borneo has experienced a complex tectonic history from the Late Cretaceous to the present and was assembled from Gondwana fragments by the early Mesozoic (Longley 1997; Moss *et al*. 1997; Cloke *et al*. 1999; Moss & Chambers 1999; Hall 2013). To the east, western Sulawesi developed in a continental margin setting during the Late Cretaceous and Paleogene (e.g. Parkinson *et al*. 1998; Hall 2012).

The Kutai Basin of eastern Borneo (the Indonesian province of Kalimantan) is the largest and deepest basin in Indonesia. Basin development commenced in the Paleogene (middle Eocene) with subsequent late Eocene – early Oligocene deltaic to marine siliciclastic deposition in the Mahakam Delta depocentre with major lowstand influxes during the middle to late Miocene in the deep-water Makassar Strait (Fraser *et al*. 2003; Saller *et al*. 2004). Chronostratigraphy of the Kutai Basin and Makassar Strait (the deep-water portion outboard of the Mahakam Delta is also known as the North Makassar Basin) is shown as Figure 6.

Western Sulawesi forms the (rifted) continental margin of eastern Sundaland and comprises microcontinental fragments together with abundant Cenozoic calc-alkaline igneous (volcanic and intrusive) rocks (Hall 2002; Nugraha *et al*. 2022; Baillie & Decker 2022). In the Lariang–Karama region (Fig. 7), all the Neogene sediments that unconformably overlie pre-Neogene rocks were considered to belong to the 'Celebes Molasse' comprising early to late Miocene shallow marine carbonate and mudstone overlain by early Pliocene shelf sediments and the Plio-Pleistocene syn-orogenic Pasangkayu Formation (Calvert & Hall 2007). Nugraha

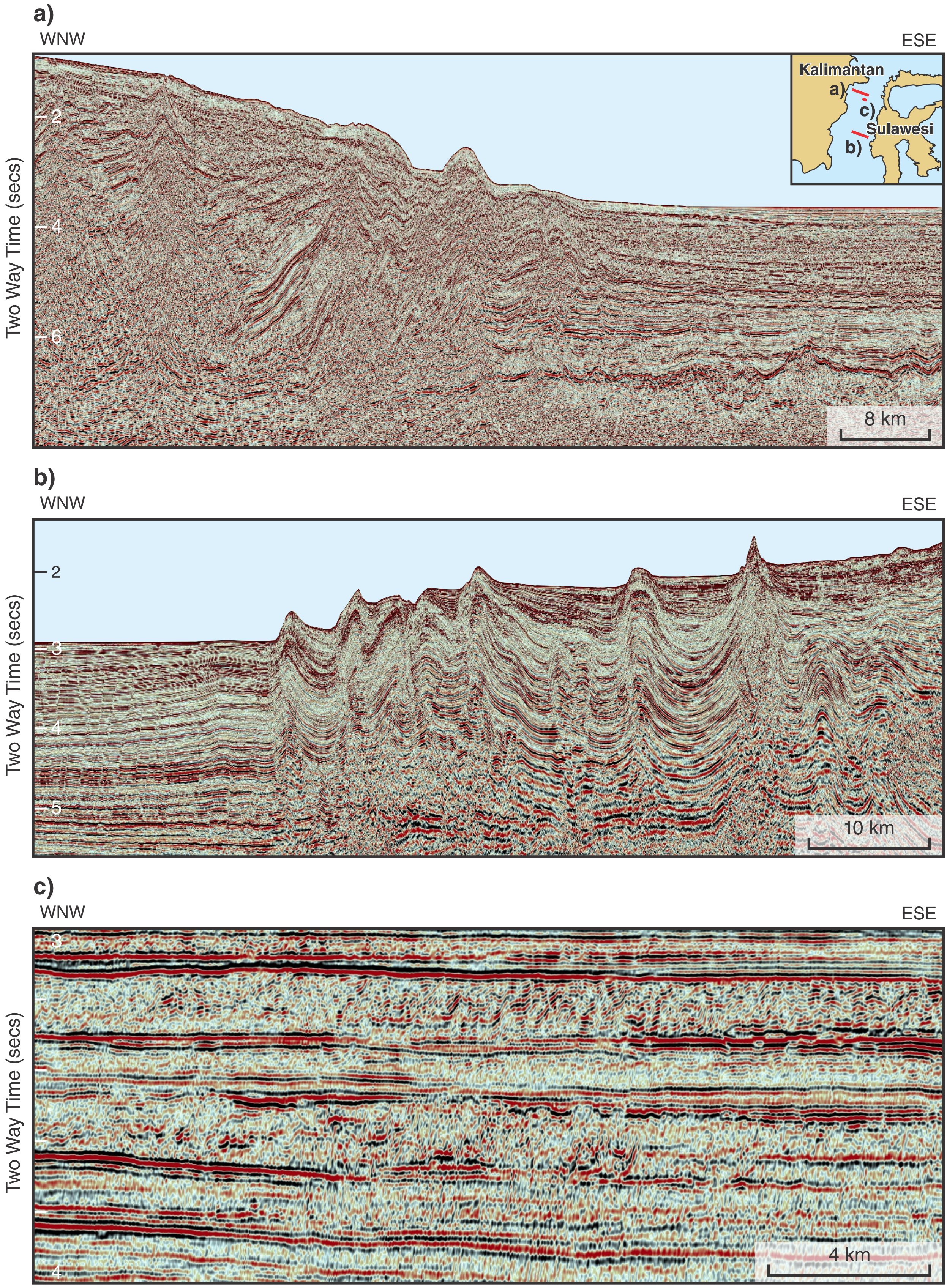

Figure 3. Makassar Strait seismic images: a) outer part of Mahakam Delta showing large growth faults, outer fold-and-thrust belt; abyssal plain with prominent acoustic basement reflector with conical features interpreted as volcanic edifices (after Baillie *et al*. 1999); b) West Sulawesi Fold Belt; c) central Makassar Strait with mass transport deposits at several horizons (after Baillie & Decker 2012).

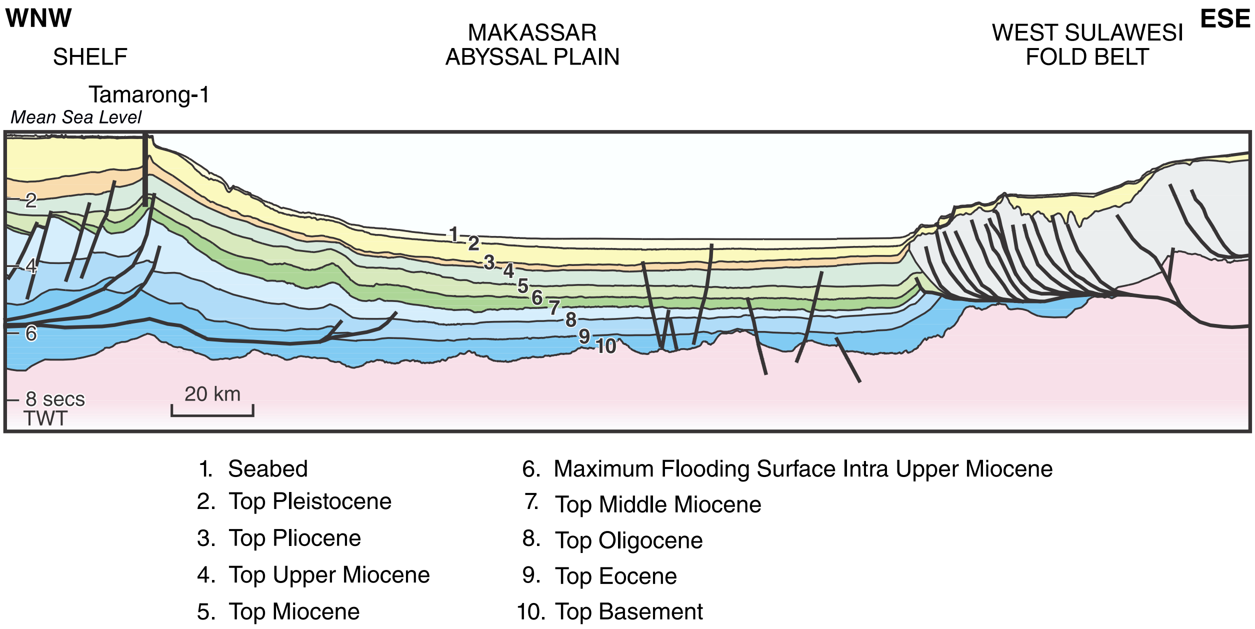

Figure 4. Makassar Strait geoseismic section though Tamarong1 well to west Sulawesi (modified after Fraser *et al*. 2003); approximate location shown as Line A–B on Figure 1.

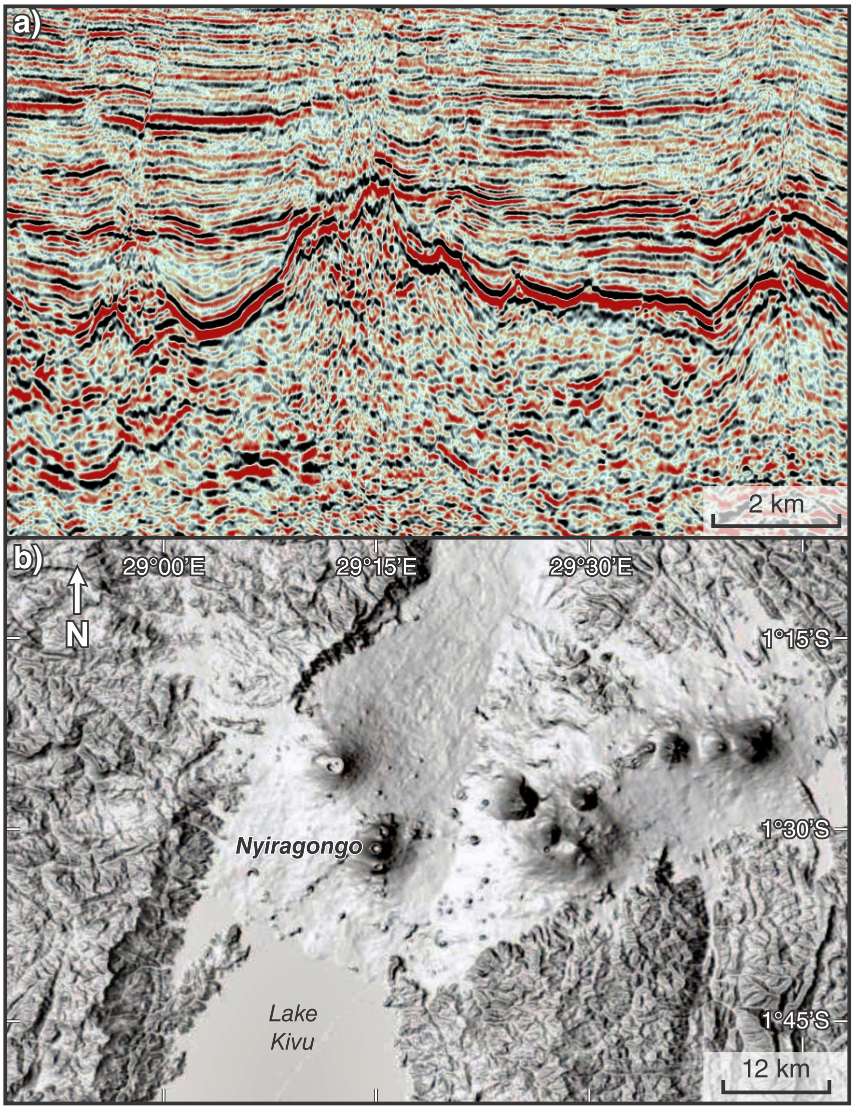

Figure 5. a) seismic section (detail of Fig. 3a) showing prominent basement reflector interpreted as a volcanic feature; b) Google Earth image (SRTM) of Lake Kiva (East African Rift) showing modern volcanoes that are possible (subaerial) analogues of Makassar volcanic features.

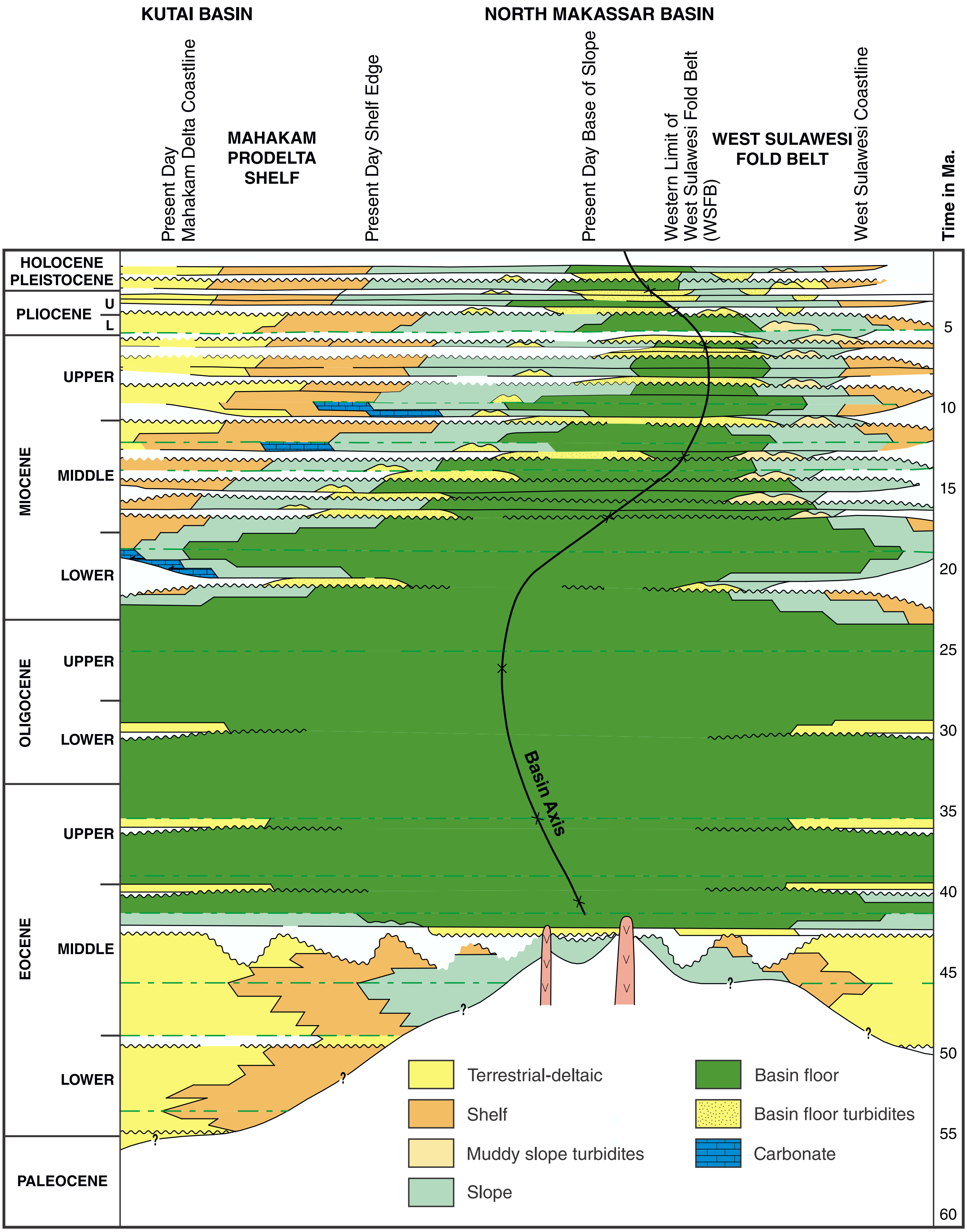

Figure 6. Makassar Strait chronostratigraphy (after Fraser *et al*. 2003).

et al. (2022) provided a new stratigraphy for the Celebes Molasse with sediments showing significant variations in age and depositional environment, and identified unconformities ranging in age from early Miocene to Pleistocene.

MAKASSAR STRAIT MORPHOTECTONIC UNITS

Paternoster Platform

The Paternoster Platform is a shallow-water (less than 200 m deep) area of basement rocks overlain by a veneer of Cenozoic shelf-margin carbonates and patch reefs, lowstand clastic sediments, and highstand muds. It forms the southern boundary of the Makassar Strait (Fig. 2). Seismic lines across the northern margin of the Paternoster Platform indicate at least 1 km of subsidence on reactivated faults close to Sulawesi in the north of the basin at the end of the Miocene (Hall 2011). There is a deep channel between the platform and South Sulawesi (Fig. 2).

The Mahakam Delta

The Mahakam Delta is a major depocentre containing over 14 km of fluvio-deltaic sediment, which started accumulating in the Oligocene; and represents the bulk since the main phase of clastic sedimentation commenced in the early to middle Miocene (van de Weerd & Armin 1992; Moss *et al*. 1997; Allen & Chambers 1998). The delta is characterised by an onshore proximal deformed zone, the modern delta and shallow shelf, a zone dominated by growth faults that may extend down the delta slope, and a deep-water outer zone of folding and associated thrust faults, leading to the abyssal plain (Fig. 4a; Moss *et al*. 2000). The current delta is dominated by fluvial and tidal processes with low wave energy (Allen 1996).

Northwest-directed contractional deformation, producing reactivation and inversion of older extensional faults, began around 14 Ma and continues to the present (Moss *et al*. 2000; McClay *et al*. 2000). The Mahakam fold belt ('Samarinda Anticlinorium') is characterised by tight, asymmetric anticlines separated by broad synclines cored by over-pressured shales and formed by contractional reactivation of early delta-top extensional growth faults. The axial traces of these structures are long (20–50 km in strike length) and linear to gently curved. Formation of the fold belt caused the Mahakam River to incise across the structures and thus become 'locked', which also diminished the influence of fluvial floods in the delta (Allen & Chambers 1998). The contraction has produced inversion and uplift of the western part of the Mahakam Delta, and caused reactivation of extensional growth faults in outer parts of the delta to produce detached, uplifted anticlines, as well as tightening and amplifying the delta-toe fold-and-thrust belt (McClay *et al*. 2000; Fraser *et al*. 2003).

The Makassar Abyssal Plain

The seafloor in the central Makassar Strait is relatively flat and undeformed; it dips gently to the north with few or no structural features (Fig. 2). In the deepest part, the north, the water depth is approximately 2,500 m. The sedimentary section underlying the northern sector of the Makassar abyssal plain (also known as the North Makassar Basin) is contiguous with the Kutai Basin (Mahakam Delta) to the west (Fig. 6). The sedimentary history of the abyssal plain is discussed below.

The West Sulawesi Fold Belt

In the eastern Makassar Strait, the seafloor shallows towards western Sulawesi where a fold-and-thrust belt is currently emerging (West Sulawesi Fold Belt, WSFB) and extends onshore to the Palu–Koro Fault (Figs 4b, 5, 7, 8). Contraction began in Sulawesi during the early Miocene with thrusting, uplift and foreland basin development in western Sulawesi from the early Pliocene (Hall 2002). Rapid uplift and exhumation provided sediment to the broadly west-verging fold-and-thrust belt (Hall 2002, 2011) with significant volumes of sediment beginning to

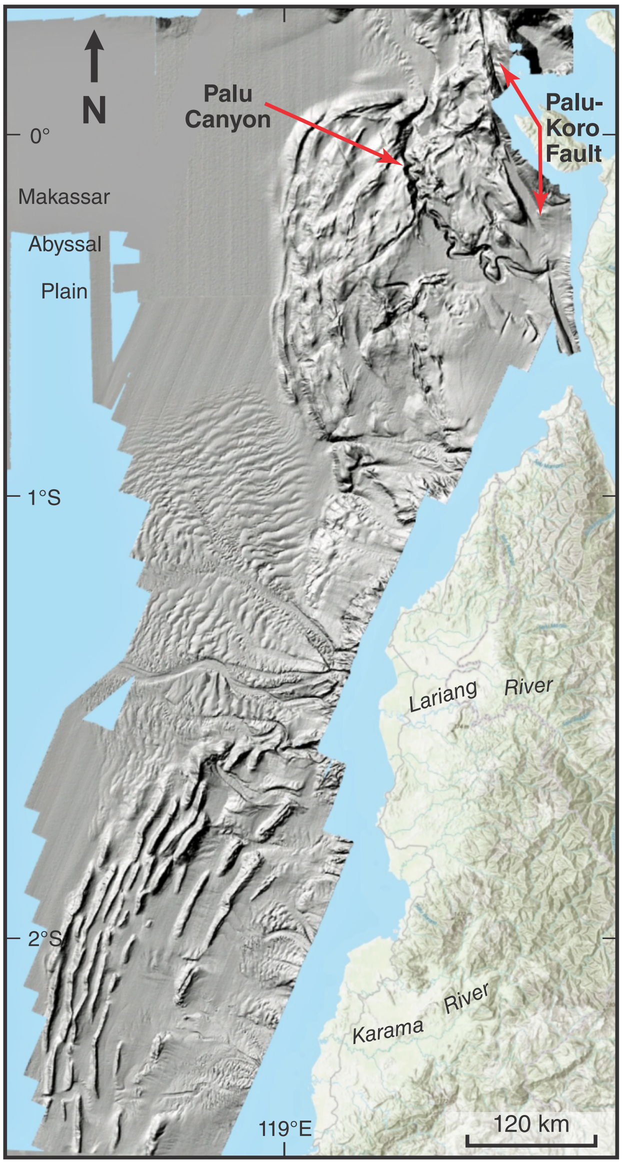

Figure 7. Bathymetric image showing offshore West Sulawesi Fold Belt.

enter the Makassar Strait from Sulawesi during the early Pliocene (Nur'Aini *et al*. 2005; Puspita *et al*. 2005).

The offshore WSFB is not a single fold belt and is divided into 3 structural provinces (Puspita *et al*. 2005). These comprise the Southern Structural Province (SSP), a west-verging thin-skinned fold-and-thrust belt with thrust faults detaching on different decollement layers; the Central Structural Province (CSP) with less deformation, at least offshore; and the Northern Structural Province (NSP), which is strongly deformed.

The age of folding is well constrained onshore where continental alluvial plain and marine deposits of the Plio-Pleistocene Pasangkayu Formation (part of the 'Celebes Molasse') formed in response to uplift of the hinterland to the east. Continuing deformation is recorded on offshore seismic sections and syn-depositional folding of younger parts of the Pasangkayu Formation (Calvert & Hall 2003, 2007; Fraser *et al*. 2003).

Northern Zone of Deformation

The Northern Zone of Deformation, a bathymetrically complex zone between the Mangkaliat Peninsula and the North Arm of Sulawesi (Fig. 1), is the southern sector of the North Sulawesi Fold-and-Thrust Belt (Tiranda & Hall *in prep*; Baillie & Decker 2022). Seismic evidence suggests several flower structures are present, representing periods of transpression along 'structural freeways' (Fraser *et al*. 2003). The Palu–Koro fault zone (Fig. 1), a NNW–SSE-trending strike–slip fault connecting with the North Sulawesi subduction trench in the Celebes Sea, is relatively active: 5 years of GPS measurements across the fault showed left lateral strike–slip movement of 3.4 cm/year with a small normal component of 0.4 cm/year (Walpersdorf & Vigny 1998).

The sinistral wrench systems are the western extremity of one of the most important and longest structural elements in the Western Pacific and Southeast Asia. The eastern end is the Sorong Fault System, which forms the southern boundary of both the Molucca Sea and the Philippine Sea plates with the Indo-Australian Plate (Hall & Wilson 2000). This fault system was initiated no later than the early Miocene by oblique convergence of the Indo-Australian and Pacific plates, and has continued to be active to the present day.

MAKASSAR STRAIT SEDIMENTARY FEATURES

The Mahakam Delta, and its resulting broad shelf, limits modern-day sedimentation from Borneo into the deep basin. Little sediment is currently being received from the Mahakam system and the main sediment flow into the deep marine basin today is from Sulawesi (Palu, Lariang and Karama rivers; Fig. 7). There is almost no shelf or delta on the Sulawesi side but 2 deep-marine fold-belt lobes trap and deflect sediment from going into the deep basin.

In the central part of the Makassar Strait, up to 4 km of sedimentary infill is present above the top synrift unconformity (Late Eocene, ~36 Ma). This section, which is entirely deep-water in origin, comprises pelagic and hemipelagic oozes and muds, sands of turbidite origin, mass-transport complexes, and carbonates. Sediment was fed into the system primarily during lowstands of relative sea level and the resultant erosion, incision and reworking of the delta plain, delta front and shelf (Moss *et al*. 2000).

Bacheller *et al*. (2011) described the stratigraphy of the deep-water Makassar Strait, as encountered in the Rangkong-1 exploration well drilled by ExxonMobil in 2009. Basement of altered continental volcanics is overlain by 2 m of deep-water carbonate of probable late Eocene to earliest Oligocene age. The succeeding highly condensed, but continuous, upper to middle bathyal, calcareous mudstones range in age from early Miocene to early Oligocene. The bulk of the section comprises an upper

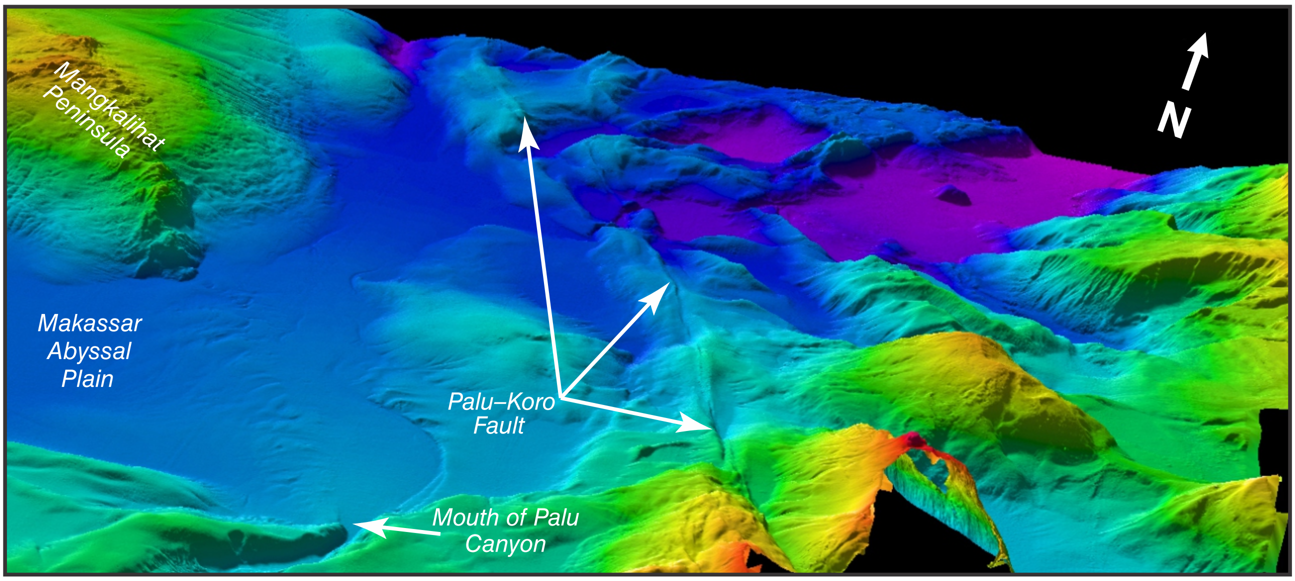

Figure 8. Rotated bathymetric image of Northern Zone of Deformation; view looking down towards the northwest; Palu–Koro fault trace indicated.

to middle bathyal distal Neogene (middle Miocene to Recent) turbiditic succession.

Turbidite sediments are both west- and east-directed; the major Borneo-derived pulse took place during the early–middle Miocene (Fig. 9), whereas Pliocene sediment was largely derived from Sulawesi. Because the Mahakam River has been locked for the past 4 million years (McClay *et al*. 2000), little coarse clastic material has entered the present Mahakam Delta and so the only material available for incorporation into west-derived turbidity currents has been material already in the system.

Makassar Fan and Sulawesi Sediment Apron

Turbidite deposition is continuing in the Makassar Strait. High-resolution bathymetric data show an active fan system—the Makassar Fan—in the central part of the basin (Fig. 10). The subtle bathymetric expression of the fan and its components are observable only via quantitative multibeam backscatter. Details of the fan are well imaged by backscatter (because of the strong returning sonar signal and the hardness and roughness of the seafloor), which allows differentiation of various sediment types subsequently confirmed by shallow coring (Fig. 10b). The Makassar Fan, which spans 65 × 50 km close to and orthogonal to the Mahakam Delta, is aggrading to the north and predominantly sourced from the Lariang River (Fig. 1) in western Sulawesi. The gradient from the channel to the end of the fan is about 0.05° and the relief across the outer fan is less than 2 m.

Interpretation of fan components from multibeam backscatter (Fig. 10c) allows recognition of:

a) a subdued outer fan with minimal relief and elongate lobes composed of interbedded sand and mud, and shallow relic channels extending nearly to the fan's limit;

b) a mid-fan with bifurcating sand-filled shallow channels generally less than 2 m deep and levees less

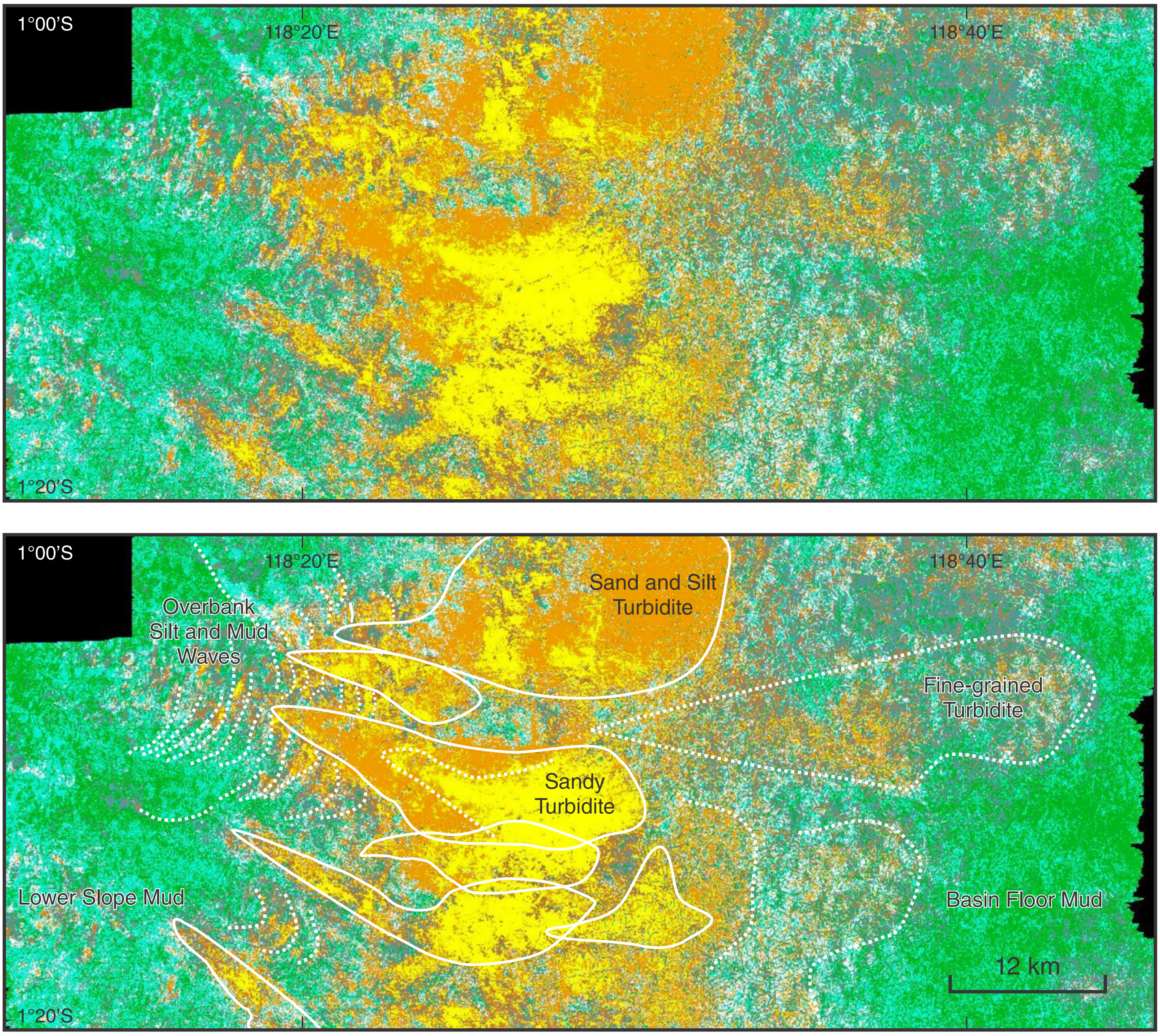

Figure 9. Uninterpreted and interpreted amplitude extraction from 3D seismic dataset showing 12 Ma turbidite sands in central Makassar Strait (after Baillie & Decker 2012); location shown on Figure 2.

than 1 m high, if present at all, with a sandy overbank and inter-channel area; and

c) an inner fan comprising a single incised straight channel up to 40 m deep with levees up to 3 m high.

The presence of sand up to coarse or medium grade was confirmed by coring (Fig. 10d–f) with the coarsest deposits being related to channels; some gravels are also present (Decker *et al*. 2008).

The fan is fed from a single channel within the basin but includes sediment almost certainly derived from both sides of the basin. It is likely that turbidites are initiated by both earthquakes and hyperpycnal currents produced when density of the water entering the basin is greater than the density of the standing water in the basin (Baillie *et al*. 2008). The hyperpycnal currents are related to climate and are triggered from high water discharge following high rainfall. The climate of South Sulawesi is tropical with 2 seasons: 'dry', from March to September, and 'rainy', from October to February; the average rainfall at the city of Makassar (formerly Ujung Pandang) is 1,000–1,500 mm/year on average.

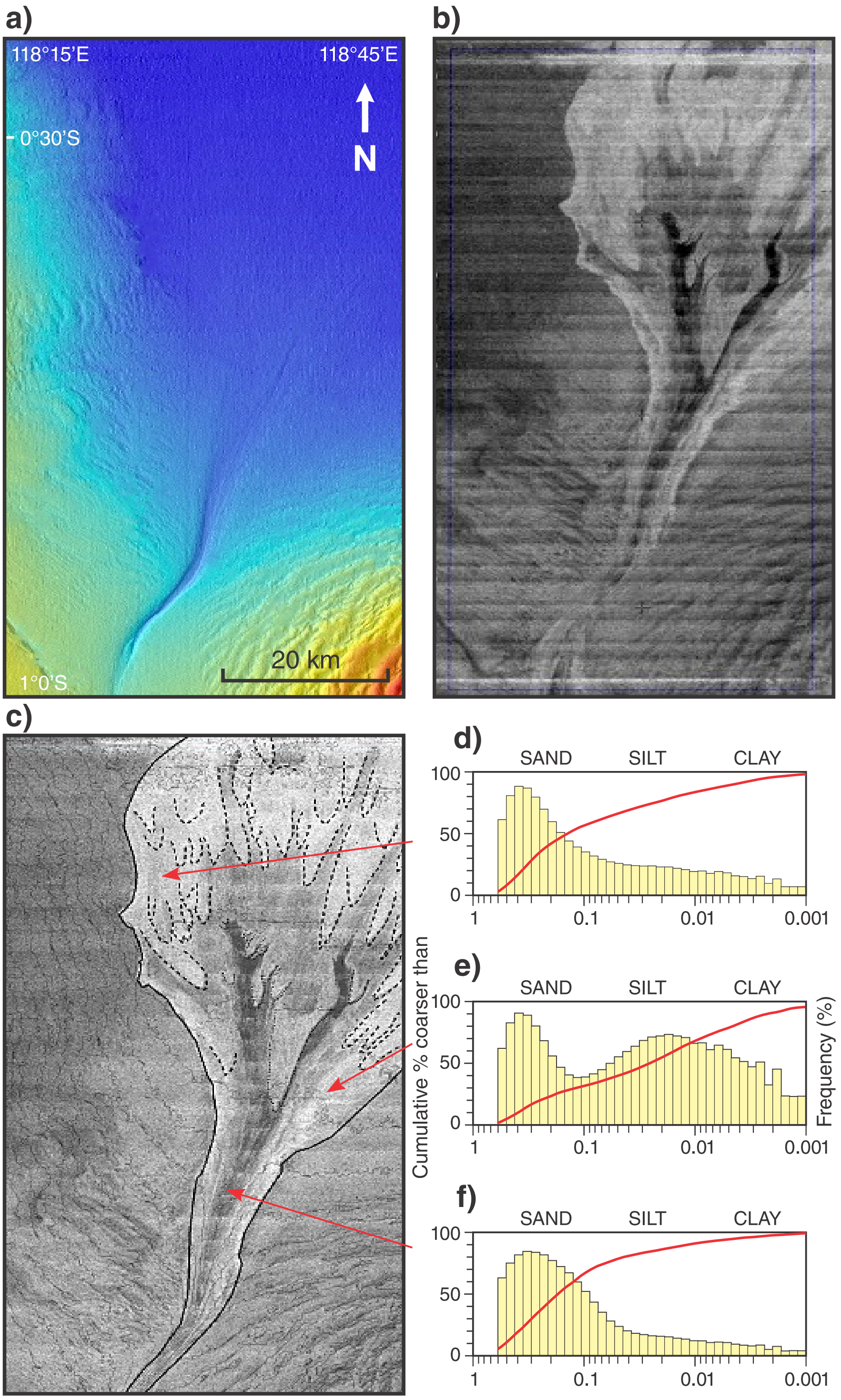

Figure 10. Makassar Fan (after Decker *et al*. 2004): a) colour-coded bathymetric image (note sand-waves in bottom (southeast) corner; b) bathymetry with greyscale backscatter; c) previous image with depositional units interpreted; d, e, f) sediment distribution curves, sample points indicated. Location shown on Figure 2.

An area with prominent sediment waves, the Sulawesi Sediment Apron, occurs east of the basin axis outboard of the Lariang River and adjacent to the Makassar Fan (Fig. 7). Coring found fine- to very-fine-grained sands and silts on the crests of the sediment waves with finer material in the troughs (Decker *et al*. 2008). Thinning of sedimentary layers occurs on the lee of individual waves.

The direction of the currents forming the sediment waves is orthogonal to the coast so a contourite origin is unlikely as sediment transport direction would be north to south and related to the Indonesia Throughflow. We believe the trigger to the formation of the Makassar Fan and Sediment Wave Field was a massive influx of sediment related to continuing tectonism in Sulawesi. As previously noted, there has been little sedimentary input into the Mahakam Delta since it became 'locked' by local tectonism during the late Miocene and therefore sediment entering the Makassar deep-water basin would largely have been recycled from the delta. With increased discharge from Sulawesi since the Pliocene, discharge from the Lariang River fed a significant volume of sediment into the basin from the east and swamped the existing submarine depositional system. The Makassar Fan developed in a northerly direction because the regional slope is to the north. Its sedimentary system is confined to the west by the Mahakam Delta and the associated small, deep-water fold-and-thrust belt (Fig. 4a), and to the east by the developing WSFB (Fig. 4b).

Mass-Transport Deposits

Mass-transport deposits (MTDs) is a general term for underwater landslide accumulations that undergo a combination of creeping, sliding, slumping and/or plastic flow in a marine or freshwater lacustrine environment to form an intergradational continuum (Nardin *et al*. 1979; Moscardelli & Wood 2008; Posamentier & Martinsen 2011). Slope-derived MTDs are readily observable on both 2D and 3D seismic data; these predominate west of the Makassar Basin's axis and throughout the deep-water sedimentary section (Fig. 4c).

Brackenridge *et al*. (2020) identified several moderate (>10 km^3) to giant (up to 650 km^3) MTDs within the North Makassar Basin Pleistocene–Recent section. Most submarine landslides that formed these deposits originated from the Mahakam pro-delta, the largest being skewed to the south.

Along the northwest margin of Borneo west of the basin axis, deep-water mass transport complexes form a large proportion of the total sedimentary column. They are not local failures but are large-scale transported deposits (Algar *et al*. 2011). South of the Paternoster Platform a large, coherent slope-attached MTD covering an area of at least 9,000 km^2 with a total volume of 2,438 km^2 has undergone relatively low internal translation and is interpreted to have been triggered by uplift of the adjacent platform area and/or basin subsidence (Armandita *et al*. 2015).

DISCUSSION AND CONCLUSIONS

The Makassar Strait is an asymmetric structural and geomorphic depression initially formed by mid-Eocene (~42 Ma) extension within a typical Sundaland continental synrift setting of graben and half-graben with common volcanoes, particularly in the northern sector. The volcanoes are probably analogous to those of the Kivu Rift (albeit subaerial) of the Great African Rift, where a combination of Cenozoic doming and crustal deformation in the eastern sector of the African Plate associated with upper-mantle activity has produced an array of hyperthermal anomalies, volcanism and local intrusions (Fig. 5b; Varet 2018).

The Makassar Strait has been the site of continuous deep-water deposition since the late Eocene with pulses of clastic sedimentation in response to tectonic events in adjacent Borneo and western Sulawesi. The sudden deepening was probably the result of extension or hyperextension related to rifting and subsequent seafloor spreading in the Celebes Sea to the north (~40 Ma; Hall, 2002). Timing of this event is constrained by the Rangkong-1 well, in which basement of altered continental volcanics is overlain by 2 m of deep-water carbonate of probable late Eocene to earliest Oligocene age (38–33 Ma; Bacheller *et al*. 2011).

Plate reorganisation around 25 Ma (latest Oligocene – earliest Miocene) caused major changes in regional tectonics and resulted in the setting up of a major left-lateral strike–slip fault system. This restructuring was responsible for transporting continental fragments along the northern margin of the Australian Plate (i.e. the Bird's Head of New Guinea) to the outer edge of Sundaland, as well as the uplift and probable rotation of Borneo, and the subsequent shedding of voluminous detritus into Neogene delta systems around the northern, western and eastern peripheries of Borneo (Hutchison 1996; Hall 2002, 2011). The increase in clastic sedimentation is expressed in the Makassar Strait through a prominent pulse of quartzose turbidites (Fig. 9).

There was a major change during the middle Miocene, around 15 Ma, when widespread extension and major subsidence began in Wallacea. Extension occurred in several phases, one of which was caused by development of the North Sulawesi subduction zone at about 5 Ma (Hall 2013). Pliocene and younger deformation in western Sulawesi was associated with metamorphism and magmatism due to extension and crustal thinning, which led to uplift in central and western Sulawesi and resultant inversion, thrusting, folding and subsidence in the WSFB (Hennig *et al*. 2016, 2017). Rapid Pliocene uplift and exhumation provided sediment to the developing fold-and-thrust belt, which has grown (and continues to grow) into a pre-existing deep-water area. The trend of fold axes indicates radial transport of material away from the mountains, which terminate relatively abruptly to the south at the northern edge of a stable carbonate platform (Hall 2011).

Continuing tectonic activity will produce geohazards, notably earthquakes and tsunamis. The Makassar Strait has the highest frequency of tsunamis in Indonesia (Prasetya *et al*. 2001). Historical records show that most are caused by earthquake-generated fault ruptures of the seafloor, except for the September 2018 Palu event, which probably had a landslide component (Jamelot *et al*. 2019). However, there are numerous other factors in the Strait that could make it susceptible to submarine landslide-triggered tsunamis, including over-steepening of the continental slope due to carbonate growth and faulting, or sediment influx from the Mahakam Delta (Brackenridge *et al*. 2020).

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