Earthquake sources of the Australian plate margin
Revised models for the 2018 national tsunami and earthquake hazard assessments

J. Griffin and G. Davies
Earthquake sources of the Australian plate margin

Revised models for the 2018 national tsunami and earthquake hazard assessments

GEOSCIENCE AUSTRALIA
RECORD 2018/31

Jonathan Griffin¹ and Gareth Davies¹

1. Geoscience Australia
Contents

1 Executive Summary .................................................................................................................. 1
2 Introduction .............................................................................................................................. 3
3 Revised submarine fault source models ................................................................................ 5
   3.1 Central and Eastern Indonesia ......................................................................................... 5
      3.1.1 Molucca Sea (Sangihe Thrust, Sangihe Backthrust and Halmahera Forearc Thrust) .... 6
      3.1.2 Cotabato Trench ...................................................................................................... 7
      3.1.3 North Sulawesi (Minahasa) Trench ......................................................................... 7
      3.1.4 Parigi and Malino Faults ......................................................................................... 7
      3.1.5 Tolo Thrust ............................................................................................................. 8
      3.1.6 Makassar Thrust ..................................................................................................... 8
      3.1.7 Banda Detachment ................................................................................................. 8
      3.1.8 Flores Thrust ........................................................................................................... 9
      3.1.9 Timor Trough ........................................................................................................ 10
      3.1.10 Semau Fault ......................................................................................................... 11
      3.1.11 Tanimbar Trough ................................................................................................. 11
      3.1.12 Aru Trough ......................................................................................................... 12
      3.1.13 Seram Thrust ........................................................................................................ 12
      3.1.14 Manokwari Trench .............................................................................................. 12
   3.2 Papua New Guinea region ............................................................................................... 13
      3.2.1 New Guinea Trench ............................................................................................... 13
      3.2.2 Manus Trench ....................................................................................................... 13
      3.2.3 Mussau Trench ..................................................................................................... 14
      3.2.4 Trobriand Trough ................................................................................................. 14
      3.2.5 Moresby (Aure) Trough ....................................................................................... 14
   3.3 New Zealand – Macquarie Island region .......................................................................... 15
      3.3.1 West South Island faults ....................................................................................... 16
      3.3.2 Puysegur Trench .................................................................................................. 16
      3.3.3 North Macquarie Ridge ........................................................................................ 16
      3.3.4 Hjort Trench ....................................................................................................... 17
   3.4 Outer-rise events ............................................................................................................. 17
   3.5 Accompanying data files and summary of fault sources ............................................... 18
4 Plate boundary and continental margin seismic source characterisation for NSHA18 .......... 20
   4.1 Indonesian shallow crustal sources ............................................................................... 21
      4.1.1 Tarera-Aiduna Fault System .................................................................................. 21
      4.1.2 Wapoga ............................................................................................................... 21
      4.1.3 Wandamen-Ransiki Fault Zone ........................................................................... 21
      4.1.4 Lengguru ............................................................................................................. 21
      4.1.5 Cendrawasih ....................................................................................................... 21
      4.1.6 Waropen .............................................................................................................. 22
      4.1.7 Nusa Tenggara Shallow ....................................................................................... 22
      4.1.8 Banda Sea ............................................................................................................ 22
      4.1.9 West Banda Sea ................................................................................................. 22
1 Executive Summary

Located within an intraplate setting, continental Australia has a relatively low rate of seismicity compared with its surrounding plate boundary regions. However, the plate boundaries to the north and east of Australia host significant earthquakes that can impact Australia. Large plate boundary earthquakes have historically generated damaging ground shaking in northern Australia, including Darwin. Large submarine earthquakes have historically generated tsunami impacting the coastline of Australia.

Previous studies of tsunami hazard in Australia have focussed on the threat from major subduction zones such as the Sunda and Kermadec Arcs. Although still subject to uncertainty, our understanding of the location, geometry and convergence rates of these subduction zones is established by global tectonic models. Conversely, actively deforming regions in central and eastern Indonesia, the Papua New Guinea region and the Macquarie Ridge region are less well defined, with deformation being more continuous and less easily partitioned onto discrete known structures. A number of recently published geological, geodetic and seismological studies are providing new insights into present-day active tectonics of these regions, providing a basis for updating earthquake source models for earthquake and tsunami hazard assessment.

This report details updates to earthquake source models in active tectonic regions along the Australian plate boundary, with a primary focus on regions to the north of Australia, and a subsidiary focus on the Puyesgu-Macquarie Ridge-Hjort plate boundary south of New Zealand. The motivation for updating these source models is threefold:

1. To update regional source models for the 2018 revision of the Australian probabilistic tsunami hazard assessment (PTHA18);
2. To update regional source models for the 2018 revision of the Australian national seismic hazard assessment (NSHA18); and
3. To provide an updated database of earthquake source models for tsunami hazard assessment in central and eastern Indonesia, in support of work funded through the Department of Foreign Affairs and Trade (DFAT) DMInnovation program.

This report presents the geological, geodetic and seismological evidence for each earthquake source’s existence, geometry, style of faulting and slip-rate, resulting in inclusion of a number of fault sources not considered in previous PTHAs for Australia. Accompanying shapefiles provide source traces and a basic parameterisation of dip, style of faulting and slip-rate. Along with the submarine fault systems relevant to tsunami hazard assessment, area source zones are developed to capture background seismicity for inclusion in the NSHA18 source model. Background zones include sources for shallow active tectonic regions that are not covered by the fault source model; intraslab sources that capture intermediate depth to deep seismicity within subducted oceanic crust; and source zones for continental margin and oceanic regions extending from the plate boundary to the edge of seismic source models developed for the Australian continent.

The representation of the sources in PTHA18 and NSHA18 necessarily involves a degree of schematisation to be suitable for modelling. This report does not present these schematisations, as in each case these are dependent on the respective hazard modelling frameworks used. Rather, the intention of this report is to describe the major features of each source and the evidence for its
seismogenic potential, providing a base level parameterisation from which the PTHA18 and NSHA18 source models are developed. Details of model implementation, including schematisation of fault geometries and calculation of earthquake magnitude-frequency distributions, are contained in the relevant PTHA18 and NSHA18 reports (Davies & Griffin, 2018; Allen et al., 2018).

A key difference between the source model developed for PTHA18 and that used for previous PTHAs in the region is greater inclusion of non-subduction-megathrust sources. This includes large-scale extensional faults associated with subduction rollback, such as the Banda Detachment in eastern Indonesia, that have the potential to host large earthquakes that can cause significant vertical deformation of the ocean floor and therefore generate tsunami. Transpressional systems, such as Macquarie Ridge, may also generate tsunami and are included in a schematised manner. Furthermore, outer-rise normal faulting earthquakes are considered in a systematic manner for subduction zones nearby Australia, the first time such a model has been developed for a PTHA.

NSHA18 is the first national seismic hazard assessment of Australia to include a detailed representation of earthquake sources for plate boundary regions to the north of Australia, including separation of sources for active shallow crustal faults, subduction interface and subduction intraslab earthquakes. In contrast, the 2012 National Seismic Hazard Model (NSHM12) only included three broad sources zone encompassing the plate boundary region, and did not discriminate between deep and shallow sources. An improved representation of these sources is expected to result in more accurate hazard assessments for northern Australia.
2 Introduction

The plate boundary regions to the north of Australia are complex and defy subdivision into easily
defined tectonic plates (Hall, 2018). Similarly, the Macquarie Ridge region exhibits a broad zone of
tectonic deformation rather than being a simple plate boundary structure (Hayes et al., 2009).
Nevertheless, a body of recent geological, geodetic and seismological studies is providing insights into
the tectonics of these regions, resulting in a revision of earthquake source models compared with
previous PTHA (Burbidge et al., 2008a; 2008b; Horspool et al., 2014; Davies et al., 2017). While major
subduction zones, such as the Sunda and Kermadec Arcs, are defined by global datasets (i.e. Bird
2003; Hayes et al. 2012; Berryman et al. 2015, Hayes et al. 2018) and are not discussed in this report,
many less significant structures have either only recently been identified, or have been subject to
conflicting interpretations. The updated earthquake source model presented here includes a number
of faults not included in past earthquake and tsunami hazard assessments undertaken in the region,
including extensional systems such as the recently identified Banda Detachment and transpressional
systems such as the Macquarie Ridge. Slip-rates for a number of faults are updated based on recent
geodetic studies. For the purposes of tsunami hazard assessment, for the first time outer-rise
earthquakes are considered for all major subduction zones surrounding Australia.

It should be noted that in some regions, in particular the Banda Sea and the Solomon Sea regions,
existing tectonic models still contain a high degree of uncertainty about the major structures
accommodating plate motions, and alternative models provided by different authors may not be
compatible. It is not the purpose of this study to resolve these outstanding issues; however, as we rely
on a wide range of models presented in the literature, in some cases our model contains fault source
models that conflict with each other in terms of style of faulting and sense of slip. Of particular note,
connections between the convergent Flores-Wetar Thrust and the extensional Banda Detachment are
unknown, and the fault sources provided here contain a geologically unlikely juxtaposition of
convergent and extensional systems. Further work will be needed to provide a more coherent tectonic
model for this region.

This report begins with a description of the updated fault source models, focusing on the geometry,
sense of faulting and slip-rates of submarine faults relevant to tsunami hazard assessment (Section
3). This is primarily based on a review of existing literature providing the evidence for the
interpretations used to develop our source models. Where available, Euler Poles reported from
geodetic studies are used to calculate relative slip-rates along strike of each fault. Base level data of
the fault trace, dip and slip-rate are provided in shapefiles accompanying this report. These fault
source models are further schematised to develop inputs for earthquake and tsunami hazard
assessment within the PTHA18 and NSHA18 projects. A summary of which faults are included in
these hazard assessments is presented in Section 3.5. For further details of these schematisations,
the reader is directed to the respective PTHA18 and NSHA18 reports (Davies & Griffin, 2018; Allen et
al., 2018). This is followed by development of area source models, including onshore and deep
(intraslab) earthquake sources, to be used to model regional earthquake sources for NSHA18 (Section
4). In Section 4 area source models covering continental margin and oceanic regions are also
described, followed by an outline of the methodology used to stitch offshore sources to the various
source models defined for continental Australia to avoid gaps and overlaps in source model coverage.

During the final stages of preparation of this report, Hayes et al., (2018) released the Slab2 model of
global subduction zones. This model included slab geometries for a number of subduction zones not
included in Slab 1.0 (Hayes et al. 2012), including the North Sulawesi, Timor, New Guinea and
Puysegur subduction zones. The Slab2 models can be expected to provide better constraints on the geometry of these sources than those provided within in this report, particularly for North Sulawesi, New Guinea and Puysegur, and should provide a basis for future updates to this model. For Timor, issues of whether the megathrust interface is seismogenic, or whether thin-skinned thrusting is occurring instead (see Section 3.1.9), need to be resolved before direct application of the Slab2 model. It is also noted that Slab2 includes a model for the Molucca Sea Plate (Halmahera Slab in their schematisation), however this slab is completely subducted and does not include the thrust interfaces described in Section 3.1.1.
3 Revised submarine fault source models

3.1 Central and Eastern Indonesia

Despite the sequence of great earthquakes on the Sumatran segment of the Sunda Subduction zone since 2004, the historical record shows that tsunamis causing fatalities have occurred twice as frequently in eastern Indonesia compared with the Sunda Arc (Latief et al., 2000). The complexity of fault systems in central and eastern Indonesia means there are numerous faults capable of generating locally significant tsunami. Proximity of the region to northern Australia, and the complex bathymetry of the region, argue for careful consideration of the region for tsunami hazard assessment for both Australia and Indonesia.

The major fault systems considered in this study, and their relative slip vectors, are shown in Figure 1. This is followed by a description of the evidence for each structure’s existence, geometry and slip-rate.

![Figure 1: Major offshore faults of central and eastern Indonesia. Arrows show motion of the hanging wall relative to the footwall derived from geodetic studies discussed in the main text.](image.png)
3.1.1 Molucca Sea (Sangihe Thrust, Sangihe Backthrust and Halmahera Forearc Thrust)

Double subduction of the Molucca Sea Plate beneath the Sangihe Arc to the west and the Halmahera Arc to the east has seen the two accretionary wedges collide in the Molucca Sea Collision Complex, with the Molucca Sea Plate being completely subducted and the Sangihe Forearc being thrust eastwards over the Halmahera Forearc (Silver & Moore, 1978; Moore & Silver, 1983; Rangin & Silver, 1990; Hall & Smyth, 2008; Rangin et al., 1996; Lallemand et al., 1998). Very high seismicity rates are observed at both shallow and deep depths, with shallow seismicity concentrated through the central part of the collision zone (McCaffrey, 1982). Various interpretations of the main structural features have been made; previous PSHAs (Irsyam et al., 2010) and PTHAs (Horspool et al., 2014) have modelled seismicity on two opposing thrusts following bathymetric lows on the west and east margins of the Molucca Sea and dipping towards the centre of the system, and appear to be based on early interpretations that suggested the colliding accretionary wedges of the two arcs were being thrust back onto their respective forearcs (Silver & Moore, 1978; Moore & Silver, 1983). Interpretations aided by additional geomorphic and geological data (Rangin et al., 1996; Lallemand et al., 1998; Hall & Smyth, 2008) suggest that the bulk of the convergence is accommodated by subduction of the Halmahera Arc beneath the Sangihe Arc; additional thrusts occur to the west, where parts of the Sangihe accretionary wedge are being backthrust onto the Sangihe Forearc, and to the east thrusting also occurs within the Halmahera Forearc south of ~3°N. To the north near the Snellius Ridge, the Halmahera Arc is almost completely subducted. Other less significant thrusts are visible in swath bathymetry (Rangin et al., 1996).

The system accommodates 80 mm/yr of the 105 mm/yr convergence between the Philippine Sea Plate and Sundaland (Rangin et al., 1999). It is unclear how the convergence is accommodated within the collision zone between the two main thrusts, other related thrust faults, and the Philippine and Cotabato Trenches to the east and west respectively. Interpretations of bathymetric data, seismic reflection profiles and seismicity suggest that convergence within the collision zone decreases north of 4°N and is increasingly accommodated by the Cotabato and Philippine Subduction Zones (Moore et al., 1981; Rangin et al., 1996; Lallemand et al., 1998). Geodetic results from Tabei et al. (2008) reported in Ohkura et al. (2015) give a rate of 26 mm/yr on the southern segment of their West Molucca Thrust (our Sangihe Backthrust) decreasing to 17 mm/yr to the north, and a rate of 58 mm/yr on their East Molucca Thrust (our Sangihe Thrust and Halmahera Thrust). Unfortunately the original results (Tabei et al., 2008) are not available, therefore we estimate the convergence azimuth from figures presented in Ohkura et al. (2015). We assume slip-rates on the Sangihe Backthrust continue to decrease further north as convergence is accommodated on the Cotabato Thrust. As the bulk of seismicity appears to be occurring on the Sangihe Thrust, and very little is associated with the Halmahera Thrust, we put the bulk of the convergence (53 mm/yr) on the Sangihe Thrust and the remainder (5 mm/yr) on the Halmahera Thrust. Furthermore, as the main crustal structure, we extend the seismogenic depth of the Sangihe Thrust to 40 km while the Sangihe Backthrust and Halmahera Thrust have seismogenic depths of 30 km. It is noted that due to uncertainty in earthquake locations and difficulty discriminating earthquakes occurring within the folded Molucca Sea Plate from those on the thrust faults of interest, these depths are estimates only. Due to its relatively small size, low slip-rate and location far from Australia, the Halmahera Thrust is not included in the PTHA18 source model.

Sediments from the colliding wedges are being extruded to the south (Silver & Moore, 1978; Moore & Silver, 1983) and show a chaotic structure indicative of continuous deformation distributed across many small faults and folds rather than localised on large crustal structures (Watkinson et al., 2011). Tsunamigenic earthquakes are likely to happen here too. However, as there are no large scale structures it is expected to be of limited significance for Australian tsunami hazard.
3.1.2 Cotabato Trench

The Cotabato Trench has formed recently in response to completion of collision of the northern part of the Sangihe and Talaud/Halmahera Arcs (especially around Mindanao) with convergence now being accommodated on the Cotabato Trench to the west and the Philippine Trench to the east (Moore et al., 1981). Subduction is established to the north while incipient subduction occurs at the southern end of the trench to about the latitude of Sangihe Island (Silver & Moore, 1978). Slip rates of 25 mm/yr across an east-west azimuth are taken from the results of Tabei et al. (2008) presented in Ohkura et al. (2015). A concave down megathrust geometry with a maximum seismogenic depth of 40 km is assumed. This is a conservative estimate, and the true seismogenic depth of the interface may be shallower, particularly in the south, as subduction has only been initiated relatively recently and seismic reflection profiles don’t show a clearly defined megathrust interface extending to depth (Schlüter & Fritsch, 1985; Hall, 2018). However, seismicity show the slab extends to depths of < 100 km, providing some support for our choice (Hall, 2018). Seismic reflection profiles suggest sub-horizontal dip at shallow depths, increasing with depth (concave down) but with dip being poorly constrained. This source is considered unlikely to generate a tsunami with significant impacts on the Australian coastline, and so is not included in the PTHA18.

3.1.3 North Sulawesi (Minahasa) Trench

The North Sulawesi Trench marks the subduction of the Sulu Sea beneath the north arm of Sulawesi. The north arm is rotating rapidly clockwise relative to the stable Sunda Block and there are large variations in slip-rate and dip along strike (Silver et al., 1983a; 1983b; Socquet et al., 2006; Cipta et al., 2016). Furthermore, the northern arm of Sulawesi can be divided into two rigid blocks separated by the strike-slip Gorontalo Fault (Socquet et al., 2006) As noted by Cipta et al. (2016) contemporary seismicity is located down-dip 50-100 km south of the bathymetric expression of the trench. However, they caution against assuming the shallow dipping up-dip portion of the megathrust is aseismic. Therefore we allow rupture all the way to the trench and vary slip-rate along the strike of the megathrust using the Euler poles of Socquet et al. (2006). Dip at a depth of 20 km (18-24°) is estimated from Cipta et al.’s (2016) analysis of earthquake focal mechanisms while dips near the trench (2-16°) are taken from Silver et al.’s (1983b) analysis of seismic reflection profiles. Dip steepens to the east. A maximum locking depth of 50 km is used and slip-rate decreases from 50 mm/yr in the west to 15 mm/yr in the east (Socquet et al., 2006). The westerly junction with the Palu-Koro Fault and the Makassar Thrust is poorly defined, and the boundary likely complex, therefore for local tsunami hazard assessment additional thrust sources would need to be defined to capture historical events such as the $M_w$ 7.8 1996 Toli-Toli earthquake that generated a locally significant tsunami and occurred shoreward of the mapped megathrust (Pelinovsky, 1996).

3.1.4 Parigi and Malino Faults

North-directed subduction rollback of the North Sulawesi Trench is accompanied by high rates of extension across the Gulf of Tomini (Advokaat et al., 2017; Hall, 2018). This extension has generated dramatic variations in topography ranging from 2-3 km high mountains along the northern arm and neck of Sulawesi to depths approaching 2 km in the Gulf of Tomini over distances on the order of 50 km (Hall, 2011). Extension is accommodated on gently dipping detachments in Central Sulawesi (Spencer, 2011), and the Parigi and Malino Faults bounding the south-west and north-west coasts of the Gulf of Tomini respectively (Watkinson & Hall, 2016). The strike-slip Tambarana Fault runs sub-parallel to the Palu-Koro Fault, between the Parigi and Malino Faults (Watkinson & Hall, 2016; Advokaat et al., 2017). Normal faulting on the Parigi and Malino Faults is expected to be locally
significant for tsunami hazard, but not to pose a threat to the Australian coastline. Therefore these sources are not included in the source model for the PTHA18.

A $M_w$ 7.7 earthquake on 20 May 1938 generated a local tsunami of up to 3 m height at Parigi, on the east coast of the neck of Sulawesi, and is thought to have occurred on the Parigi Fault (Griffin et al., 2017). In the absence of further information on their structure, both the Parigi and Malino Faults are modelled as shallow dipping (30°) normal faults with listric geometry, extending to a maximum seismogenic depth of 25 km.

### 3.1.5 Tolo Thrust

The Tolo Thrust is offshore of the south-east margin of Sulawesi. Greatest deformation occurs in the centre of the structure, tapering to either end (Silver et al., 1983b). The northern end appears to link structurally to the onshore Matano strike-slip fault (Silver et al., 1983b). The Tolo Thrust has been proposed to represent incipient subduction by Hall (2018). Seismic reflection profiles show an extensional detachment on the landward side of the structure, with detached crust then thrust over oceanic crust of the western edge of the North Banda Sea (Hall, 2018). We model the structure as a simple thrust fault with a dip of 30° and maximum depth of 30 km. Using the results of (Koulali et al., 2016) we model a slip-rate of 14 mm/yr with an azimuth of 100°. This results in near fault-normal compression in the southern part of the Tolo Thrust transitioning to left-lateral strike-slip motion as the thrust curves in transition to the Matano Fault. We note that further work is required to better consider potential tsunamigenesis from the rotational extensional-detachment-to-thrust structures shown in seismic reflection profiles (Hall, 2018).

### 3.1.6 Makassar Thrust

Seismic reflection profiles show a series of thrust faults running north-south offshore of the west coast of Sulawesi that appear to extend and connect with the Palu-Koro Fault and North Sulawesi Subduction Zone in the north (Puspita et al., 2005). It is unclear if the Makassar Thrust should be modelled as one structure, or a series of thrusts. In this study we follow Cipta et al. (2016) who model the fault as a single thrust fault accommodating 9 mm/yr of convergence between Sulawesi and Borneo on 30° dipping thrust faults. This source is considered unlikely to generate a tsunami with significant impacts on the Australian coastline, and so is not included in the PTHA18.

### 3.1.7 Banda Detachment

Although for some time it had been hypothesised that the 7.2 km deep Weber Deep had formed due to forearc extension related to subduction rollback (e.g. Charlton et al. 1991; Spakman & Hall 2010; Hall 2011), only recently has the acquisition of industry multi-beam bathymetry data allowed for the identification of the Banda Detachment, a major crustal scale normal fault along which the Weber Deep opened (Pownall et al., 2016). This ~450 km long fault is a low angle detachment with the footwall forming the eastern slopes of the Weber Deep. The hanging wall is ~120 km to the west forming the western boundary of the basin, and it is the largest bathymetric expression of any normal fault in the world’s oceans (Pownall et al., 2016). To the north the detachment steepens and transitions into the predominantly strike-slip Kawa Shear Zone, with the orientation of the shear zone aligning with linear grooves trending 120-130° observed on the footwall of the main detachment (Pownall et al., 2016). It is assumed based on GEBCO 2014 bathymetry grid (www.gebco.net) and seismicity that the southern end of the detachment also transitions to a strike-slip system, although this is not confirmed. Low angle (~12°) fault planes in south-east Seram and Pulau Fadol are
interpreted as the surface expression of the Banda Detachment (Pownall et al., 2016). We interpret the detachment interface to be a low-angle normal fault in the centre of the basin, steepening to oblique strike-slip structures to the north and south. Due to the consistent sub-parallel orientation of fault plane grooves and the Kawa Shear Zone we model slip azimuth increasing over the range 120-130° from north to south. Subduction rollback along this orientation since ~2 Ma has opened the basin by 120 km, implying an average 60 mm/yr slip-rate over this period.

Thin sedimentary cover within the basin suggest it is very young and that rapid subsidence has occurred (Pownall et al., 2016). There is no instrumental seismicity to indicate whether the Banda Detachment is active. However historical reports of two large earthquakes and tsunami that struck the Banda Sea (including the Banda Islands and Ambon) in 1649 and 1852 note the creation of new islands in the Kei Islands (Wichmann, 1918), which are located on the surface expression of the footwall. Although further work needs to be undertaken to determine conclusively if these earthquakes did occur on the Banda Detachment, this evidence suggests that coseismic uplift of the exposed footwall up-dip of the seismogenic zone may occur, which in turn would be expected to contribute to tsunami generation. Furthermore, due to the steep slopes of the basin and the low angle of the fault plane, horizontal coseismic deformation may also be a significant for tsunamigenesis.

High heat flow and thinned crust within the basin is expected to limit the seismogenic depth. We estimate a maximum seismogenic depth of 15 km at the centre of the basin, and 20 km to the north and south where the fault transitions into a dominantly strike-slip environment. Llistric geometry is assumed and dips at 10 km depth estimated. However, in the final PTHA18 and NSHA18 schematisations, this geometry is simplified due to constraints on modelling faults with strongly curved fault geometries and varying seismogenic depths.

Related to the Banda Detachment, multibeam bathymetry shows large (up to 100 km scale) submarine mass failure scars along the slopes bounding the Weber Deep. Although it is unknown if these scars represent single or multiple events, large scale submarine mass failures are another major source of tsunami hazard in this region. It is worth noting that the largest observable scar, at 135.5° E, 5.0° S, is located directly above the estimated hypocentre of the 1938 Mw 8.6 moderate depth (60 km) earthquake (Okal & Reymond, 2003). Other earthquakes in the Global Centroid-Moment-Tensor (GCMT) catalogue (Ekström et al., 2012) occur in this region along a NE trend at similar depths. We speculate that this may be a localised region of heightened deformation within the subducted Australian slab beneath the Banda Sea, and that these earthquakes on occasion may trigger submarine mass failures; that only a small tsunami was observed in 1938 (Okal & Reymond, 2003) suggests that for this event large mass failures did not occur.

### 3.1.8 Flores Thrust

The Flores Thrust refers to the full extent of the back-arc thrust extending from east Java, north of Bali, Lombok, Sumbawa, Flores and further east to the north of Wetar. It incorporates faults previously defined as separate segments in varying configurations, including the Kendeng Thrust Belt on east Java and extending offshore, the North Bali Back-Arc, the Flores Thrust, the Alor Thrust, the Wetar Thrust, and a number of additional smaller thrust structures (e.g. Breen et al. 1989; Silver et al. 1983; Irsyam et al. 2010; Horspool et al. 2014). Linking all of these structures together is based on geodetic block modelling (Koulali et al., 2016) and a lack of obvious structural boundaries that would prevent rupture across previously mapped back-arc segments, although fault mapping demonstrates that the back-arc is clearly structurally segmented and more complex than is practical to treat for assessing earthquake and tsunami hazard for Australia (Breen et al., 1989; Irsyam et al., 2010; 2017). Source models for the largest instrumentally recorded earthquake on this structure, the 1992 Mw 7.9 Flores
earthquake and tsunami, show that this earthquake occurred further south than the incipient trench where the Flores Thrust is mapped, further demonstrating the complexity of the region (Beckers & Lay, 1995; Hidayat et al., 1995; Imamura et al., 1995; Griffin et al., 2015). Similarly, locations for the 2018 Lombok sequence of earthquakes (28 July $M_w$ 6.4, 5 August $M_w$ 6.9 and 19 August $M_w$ 6.9) are located south of the surface trace of the Flores Thrust. However modelling the back-arc as a single structure both simplifies the modelling process and allows for the very real possibility of multi-segment ruptures (e.g. considering the 2016 $M_w$ 7.8 Kaikoura, New Zealand earthquake that ruptured at least 12 major faults; Hamling et al. 2017). A maximum locking depth of 20 km is estimated by Koulali et al. (2016), however a recent inversion for the 1992 Flores earthquake allow some slip to 30 km (Ignatius Ryan Pranantyo pers. comm.). Furthermore, United States Geological Survey locations for the 2018 Lombok sequence also range in depth from 14-31 km, and therefore we use a maximum seismogenic depth of 30 km. Slip-rates are taken from Koulali et al. (2016). Seismic reflection profiles show a mix of thrusting styles, with listric and concave downward fault planes being imaged (Silver et al., 1983c; Breen et al., 1989; Snyder et al., 1996), again reflecting the complex nature of the region. High resolution seismic reflection images from more recent studies do not exist (or are unknown to us). Maximum magnitudes can be expected to be limited by the relatively shallow locking depth compared with true subduction zones, although are likely higher than the $M_w$ 7.8 used by Irsyam et al. (2013). Horspool et al. (2014) used a maximum $M_{\text{max}}$ of $M_w$ 8.5, while Nguyen et al. (2015) and Griffin et al. (in review) estimate a moment magnitude of up to 8.4 for an earthquake that occurred on the Flores Thrust in 1820 resulting in destruction of buildings and forts due to strong ground shaking and tsunami inundation in Sumbawa and South Sulawesi (Wichmann, 1918).

### 3.1.9 Timor Trough

The Timor Trough marks the collision between Australian continental crust and the Sunda-Banda Arc. The geometry of the main fault plate is poorly constrained. Seismic imaging shows thin-skinned deformation in the Timor fold-thrust belt linking into a low angle decollement (Saqab et al., 2017), which possibly steepens again at depth (Snyder et al., 1996). The deformation front is characterised by steep shallow thrusts (~30° dip) that link into a shallow decollement (~10° dip) at depths of around 5 km (Saqab et al., 2017; Hughes et al., 1996). There are few constraints beyond this depth, however a model developed by Snyder et al. (1996) on the basis of deep seismic reflection and refraction data suggests steepening of the decollement again at depths greater than 10 km. Due to the poor constraints this geometry is simplified to a constant 25° dipping fault plane for PTHA18. A maximum seismogenic depth of 25 km is used, based on the interpretation that deformation is primarily thin-skinned, rather than subduction. A number of focal depths within the ISC-GEM catalogue (Storchak et al., 2013) also extend to these depths. Due to its relative proximity to northern Australia, it is recommended that further work be undertaken to constrain the geometry of the Timor Trough, in particular if more industry-acquired seismic reflection data (e.g. Baillie and Milne, 2014) becomes publically available.

It has been contentious as to whether significant convergence is still being accommodated at the Timor Trough. Although Baillie and Milne (2014) argue on the basis of seismic reflection profiles that the deformation front has not been active since ~4 Ma, Saqab et al. (2017) have reinterpreted these data along with additional seismic reflection data to conclude that there is ongoing activity at the deformation front. This is consistent with geodetic studies showing convergence of ~ 30 mm/yr in the west decreasing to ~10 mm/yr to the east of Timor (Bock et al., 2003; Kouali et al., 2016). Furthermore, Saqab et al. (2017) show evidence for episodic earthquake behaviour since 6 Ma and argue that present seismic quiescence should not be interpreted as low seismic hazard. Consistent with this interpretation, temporal variations in uplift rate since the Pliocene have been observed on the island of Timor (Nguyen et al., 2013). Based on this evidence we apply the slip-rates from Kouali et al.
(2016) along the margin. Further east along the Timor Trough relative motion becomes increasingly oblique and slip-rates decrease to insignificant values, before transitioning to the Tanimbar Trough in a low slip-rate, obliquely extensional regime (see Section 3.1.11 for more details). To the west we place the boundary with the Sunda Arc subduction zone at 121.6° E, as an approximation of where Australian continental crust is colliding with the trench based on interpretation of bathymetry. To the west of the boundary, Australian oceanic crust is subducted beneath the Sumba Block (being Australian continental crust accreted to Sundaland during the Late Cretaceous) while to the east thin-skinned deformation is occurring in the foreland basin resulting from Miocene collision of the Australian continent (Timor) with the Sunda-Banda Arc (Hall & Sevastjanova, 2012; Saqab et al., 2017). The exact location of the boundary is poorly determined. To the east, the intersection of the Semau Fault (123° E), marking the boundary between the Sumba and Timor blocks defined by Koulali et al. (2016), could instead mark the transition from subduction to thin-skinned deformation. Further to the west the depth of the trough increases, and the boundary could alternatively be placed south of Sumba (at ~120° E), as here depths reach typical Java Trench depths of greater than 5000 m and there is increased seismic activity.

Saqab et al. (2017) also found that there is ongoing extensional deformation due to flexural bending of the Australian plate to the south of the Timor Trough. Although these faults are found in much shallower water than the Timor Trough, the potential for outer-rise earthquakes as a source of tsunami hazard may also need to be considered.

3.1.10 Semau Fault

This fault marks the boundary between the Sumba and Timor blocks in Koulali et al.’s (2016) geodetic model. As it is predominantly a strike-slip fault, with the majority of the fault located onshore in West Timor and to the north of Timor in the Ombai Strait, it is not considered significant for tsunami generation for Australia, and therefore not included in PTHA18, while for NSHA18 this source is included within an area source zone.

3.1.11 Tanimbar Trough

Structurally the Tanimbar Trough is the north-eastward continuation of the Timor Trough however it is separated due to a transition from convergence to divergence evidenced by interpretation of seismic reflection profiles, focal mechanisms and consideration of regional tectonics (Schlüter & Fritsch, 1985; Charlton et al., 1991). Divergence is re-activating thrusts formed before the cessation of subduction. Recent geodetic studies suggest left-lateral strike-slip motion with oblique convergence in the southern segment and extension in the north (Koulali et al., 2016). Motion is poorly constrained with the island of Tual moving relative to Australia at an insignificant rate of 1.0 +/- 1.7 mm/yr, meaning extension in the southern segment is still consistent with geodetic data. The oblique motion transitions to predominantly extensional in the Aru Trough to the north (Charlton et al., 1991). The most updip region near the trough is mostly aseismic for the instrumental period; a few moderate-magnitude earthquakes have occurred at depths of 20-40 km. The GCMT catalogue shows a transition from thrust dominant to mostly normal mechanisms east of about 131° E. The weight of evidence therefore supports modelling the feature as divergent rather than convergent, with low slip-rates, and recognising that there is a significant strike-slip component of motion. For this study the Tanimbar Trough is modelled as a ~145 km long segment with the extensional component of the oblique slip considered tsunamigenic, and having low slip-rates of < 2 mm/yr. The boundary between the Timor and Tanimbar Trough segments is put at 130.7° E, the approximate location of changes in fault orientation and focal mechanism. It is assumed following the interpretation of seismic lines from
Schlüter & Fritsch (1985) presented in (Charlton et al., 1991) that earthquakes occur on thrusts within the accretionary wedge reactivated as low-angle normal faults, rather than the low angle former megathrust. Therefore a listric geometry is assumed with a 30° dip at the surface and a 5° dip at 20 km depth. We note that our interpretation conflicts with Liu and Harris (2014) who attribute the destructive 1852 Banda Sea Tsunami to a large megathrust earthquake on the Tanimbar Trough; in our opinion other structures such as the Banda Detachment may be more plausible sources for this event, although work to resolve this problem is ongoing.

3.1.12 Aru Trough

The Aru Trough is a zone of approximately east-west extension bounded to the north by the Tarera-Aiduna Fault System and linking to the south to the Tanimbar Trough segment of the Timor Trough/Banda Arc. Charlton et al. (1991) interpret the active zone of extension to be on the eastern side of the trough due to the concentration of seismicity. They estimate 35 km of extension since the Pliocene. If we assume that extension initiated ~ 2.5 Ma then we can estimate a long-term slip-rate of 14 mm/yr. Geodetic measurements from Bock et al. (2003) and Stevens et al. (2013) provide a further constraint with extension rates of 17.6 mm/yr, azimuth 85.7° and 22.5 mm/yr, azimuth 88.0° respectively. We favour the use of the Stevens et al. (2013) solution as this has the longest period of geodetic observations available. Seismic reflection profiles show high angle normal faults bounding the trough (Jongsma et al., 1989) and extending to depths of more than 10 km (Granath et al., 2010), without resolution of the faults at greater depths. We place our source on the eastern side of the trough and assume a dip of 60° to the west. Earthquakes have been observed from shallow crustal to upper mantle depths (Sloan & Jackson, 2012). For the purpose of the PTHA18 we assume a maximum seismogenic depth of 32 km, consistent with estimates of crustal thickness (Jacobson et al., 1979), as deeper earthquakes in the upper mantle are not expected to be significant for tsunami generation. A constant dip of 60° places the down-dip limit of the fault approximately in the centre of the ~35 km wide Trough and is a reasonable approximation to the fault geometry, although the dip may well be shallower at depth.

3.1.13 Seram Thrust

The Seram Fold Thrust belt accommodates ~20 mm/yr convergence (Rangin et al., 1999; Stevens et al., 2002). Youthful folds on the north coast of Seram are consistent with S-dipping thrusts and are interpreted by Watkinson and Hall (2016) as consistent with the presence of an offshore megathrust.

3.1.14 Manokwari Trench

The Manokwari Trench is the western-most segment of the New Guinea Trench, offset by a transform fault ~125 km to the south of the western-most extent of the main New Guinea Trench. Seismic reflection profiles show evidence of subduction and thrusting but are not of sufficient resolution to provide good constraints on the fault geometry (Milsom et al., 1992). Analysis of the 3 January 2009 $M_s$ 7.6 and $M_w$ 7.4 doublet show dips of 31° and 28° and focal depths of 15 and 12 km respectively (Poiata et al., 2010). We assume a typical concave down subduction geometry. Okal (1999) suggests a magnitude ~8 earthquake in 1914 that generated a tsunami causing significant damage in West Papua, and also observed in Hawaii, was most likely generated on the Manokwari Trench.
3.2 Papua New Guinea region

The major fault systems and relative slip vectors, in general taken from Koulali et al. (2015) are shown in Figure 2. This is followed by a description of the evidence for each structure's existence, geometry and slip-rate.

![Figure 2: Major offshore faults of the PNG region. Arrows show motion of the hanging wall relative to the footwall derived from geodetic studies discussed in the main text.](image)

3.2.1 New Guinea Trench

Active subduction was shown to be occurring at the New Guinea Trench by Tregoning and Gorbatov (2004). Koulali et al. (2015) estimated 66 +/- 1.6 mm/yr oblique convergence across the New Guinea Trench with very low coupling decreasing from 20% in the west to 10% in the east. Geometry is taken from the Slab2 model (Hayes et al. 2018) for PTHA18, while as theNSHA18 hazard calculations were undertaken prior to the release of Slab2, a geometry based on the parameterisation presented here is used for NSHA18.

3.2.2 Manus Trench

It has previously been argued that subduction at the Manus Trench has ceased, or not begun, with no clear geological or seismological evidence of subduction. There is almost no instrumental seismicity on the structure. However GPS studies by Tregoning (2002) showed convergence to be occurring at
the Manus Trench, and a more recent study by Koulali et al. (2015) has confirmed that a small component of convergence between the North Bismark Plate and the Pacific Plate is accommodated on this structure. Euler Poles from the block model of Koulali et al. (2015) suggest oblique relative plate motion increasing from 3 mm/yr in the west to 10 mm/yr in the east. Koulali et al. (2015) suggest slip-rates of < 10 mm/yr, based on observations that a GPS site on Manus Island has a velocity of ~6 mm/yr relative to the Pacific Plate, with convergence from 3-5 +/- 1.4 mm/yr across the trench; we calculate a maximum convergence of ~ 7 mm/yr based on Koulali et al.’s (2015) Euler Pole. The absence of a volcanic arc and seismicity at depth suggests that subduction is either not occurring or not well-established at the trench; based on this interpretation we limit the seismogenic depth to 25 km, although it could be shallower, and assume a linear down-dip geometry with 30° dip.

3.2.3 Mussau Trench

The Mussau Trench is a zone of low slip-rate oblique convergence between the Caroline Sea and Pacific Plates. Oblique slip-rates of 12 mm/yr are taken from Bird (2003). Earthquake focal mechanisms show large right-lateral strike-slip components with minor thrust components, which combined with the low slip-rates across this boundary led McCaffrey (1996) to argue that the Mussau Trench may be a zone of local deformation but not a plate boundary. Absence of an active volcanic arc support interpretation that subduction is not presently occurring. With little other information available, we model the source as a thrust fault with linear down-dip geometry with 30° dip, and a maximum seismogenic depth of 25 km.

3.2.4 Trobriand Trough

Some tectonic models of the eastern New Guinea region have interpreted the Trobriand Trough as forming the southern boundary of the Solomon Sea Plate, resulting in a separate Woodlark Plate to the south (e.g. Bird, 2003). Seismic reflection profiles show that subduction was occurring up until the recent past however does not show evidence that subduction is still occurring (Lock et al., 1987). Due to the entirely submarine location of the Trobriand Trough, GPS studies have not been able to measure relative motion between the proposed Solomon Sea and Woodlark Plates, however Wallace et al. (2014) are better able to fit their GPS data without placing a boundary along the Trobriand Trough, and suggest if there is convergence here, that slip-rates are less than 2 mm/yr. Lack of seismicity and the lack of a well-defined Benioff zone further strengthens the case that subduction has ceased within the Trobriand Trough, although we cannot rule out that deformation still occurs on this structure. Therefore we include the Trobriand Trough in our source model as a crustal thrust fault with an estimated slip-rate of 1 mm/yr and maximum seismogenic depth of 30 km, in contrast to the previous Australia PTHA (Burbidge et al., 2008b) that used the Bird (2003) plate model as the basis for its source model. A linear down-dip geometry with 30° dip is assumed.

3.2.5 Moresby (Aure) Trough

The first geodetic evidence for convergence between the Papuan Peninsula and Australia across the Moresby Trough has been recently published by Koulali et al. (2015), who reported convergence on the order of 5-7 mm/yr. Further supporting its interpretation as a convergent setting, seismic reflection profiles presented by Ott and Mann (2015) show evidence of Miocene to Recent thrusting across the Moresby Trough. To the east, the Moresby Trough connects topographically with the Pocklington Trough, however a lack of seismicity has led to this feature being interpreted as a passive margin (Ott & Mann, 2015; Abers et al., 2016), or possibly undergoing slow extension due to rotation of the
Woodlark Microplate (Wallace et al., 2014; Ott & Mann, 2015). Based on this evidence we include the Moresby Trough with the slip-rates of Koulali et al. (2015) in our hazard assessments, but consider the Pocklington Trough inactive and do not include this structure as a seismogenic source. A listric geometry with maximum seismogenic depth of 30 km is assumed.

3.3 New Zealand – Macquarie Island region

The major Tonga-Kermadec-Hikurangi subduction system is modelled using standard global models (Bird, 2003; Hayes et al., 2012; Hayes et al. 2018). Revisions of fault source models are undertaken for sources offshore of the South Island of New Zealand, extending south through the Puyssegur Subduction Zone and Macquarie Ridge to the Hjort Subduction Zone. Sources in this region are important for tsunami hazard assessment in Australia, however due to the large distances from the Australian mainland, these sources are not considered significant for earthquake ground shaking hazard, and therefore not included in the NSHA18 source model.

Figure 3: Major offshore faults of the New Zealand – Macquarie Island region. Arrows show motion of the hanging wall relative to the footwall. Velocities are taken from Bird (2003).
3.3.1 West South Island faults

A series of thrust faults running just offshore of the west coast of the South Island of New Zealand have been included in recent tsunami hazard assessments for New Zealand (Power, 2013; Power et al., 2017). These faults (Barn, South Westland, Cape Foulwind, Kongahu and Kahurangi) dip to the south-east, meaning the down-dip projection of the fault plane extends onshore, reducing the tsunamigenic potential. They are modelled by Power (2013) with a characteristic magnitude of 7.6 and maximum magnitude of 8.0. Slip-rates are all $\leq 2$ mm/yr. As the bulk of the vertical surface deformation from earthquakes on these faults will occur onshore, with minor components offshore, they are not considered significant for tsunami hazard in Australia and therefore not included in the PTHA18 source model.

3.3.2 Puysegur Trench

Hayes et al. (2009) and Hayes and Furlong (2010) have shown that subduction at the Puysegur Trench occurs in the direction of relative plate motion between the Australia and Pacific Plates, and therefore obliquely to the axis of the trench. This conclusion is supported by: the orientation of earthquake slip vectors; contours of the subducted slab being normal to the direction of relative plate motion, rather than the trench axis; and a lack of obvious structures onto which trench-parallel plate motion could be accommodated. High seismicity rates within the Puysegur Block, a $\sim 150$ km wide component of deforming Australian oceanic crust located to the west of the Puysegur Trench, are evidence of deformation due to locking of the wide, shallow dipping subduction interface, in part driven by subduction of young (20-40 Ma), relatively buoyant, oceanic crust (Hayes et al., 2009). Seismicity within the Puysegur Block includes the $M_w$ 8.1 23 December 2004 strike-slip earthquake. This block is thought to be bounded to the west by a propagating tear within the Australian plate linking to the Alpine Fault in the South Island of New Zealand (Lebrun et al., 2003; Malservisi et al., 2003; Hayes et al., 2009). For the PTHA18, slip vectors are taken from Hayes and Furlong (2010), while the Slab2 model (Hayes et al., 2018) is used for the fault interface geometry.

3.3.3 North Macquarie Ridge

Between Macquarie Island and the Puysegur Trench, the boundary between the Australian and Pacific Plates exhibits a dual mode of rupture (Ruff et al., 1989), with predominant strike-slip faulting combined with occasional thrust events (Massell et al., 2000). For instance, in the GCMT catalogue (1976-2016; Ekström et al., 2012), 15 of 18 earthquakes with $M_w > 6.0$ in this region show a strike-slip focal mechanism, including the two largest earthquakes with $M_w \sim 8.1$; while the remaining three events have reverse or oblique reverse focal mechanisms, dipping towards the Australian plate at 34-52°. Two of the latter events have depths of 10 km, while the third is recorded as 33 km which is interpreted as being poorly constrained. These events are interpreted to represent thrusting along transpressional flower structures. This earthquake history is consistent with plate tectonic models that indicate oblique (predominantly transverse) plate motion with a convergent component of around 5-10 mm/year, and deformation concentrated on the Australian side of the plate boundary (Bird, 2003; Kreemer et al., 2014). McCue (2008) highlighted the potential for this region to host a tsunamigenic thrust earthquake, and Greenslade et al. (2009) included tsunami sources in this region to support the Bureau of Meteorology’s T2 scenario database for the Joint Australian Tsunami Early Warning Centre. In order to model a representative geometry of this transpressional system, we model thrust events in this region with a steeply-dipping linear source-zone geometry, having a dip of 50° towards the Australian Plate, and a maximum depth below the trench of 20 km consistent with typical oceanic lithosphere thickness.
3.3.4 Hjort Trench

Incipient easterly directed subduction of the Australian Plate beneath the Pacific Plate is occurring at the Hjort Trench. Meckel et al. (2003) have demonstrated that seismogenesis is limited to a maximum depth of 20 km. To the north, the trench transitions to the Macquarie Ridge and relative motion is increasingly oblique. We model a concave down parabolic fault plane with a dip of 10° at the surface steepening to 20° at 15 km depth. Slip-rates and fault trace are taken from global models (Bird, 2003).

3.4 Outer-rise events

Outer-rise events refer to those events that occur within the fore-arc bulge of the subducting oceanic plate due to bending and flexure of the plate as it subducts. Relatively little is known about these events, including their maximum magnitudes and recurrence intervals, compared with megathrust events. Outer-rise earthquakes may have normal fault mechanisms due to extension caused by bending of the plate and pull of the subducted slab; however thrust earthquakes also occur, and are thought to be linked to locking at the subduction interface (Christensen & Ruff, 1988). In some cases, outer-rise events may be associated in time with megathrust events (Lay et al., 2010; Lay et al., 2009). A Mw 8.3 outer-rise earthquake occurred to the south of Sumba in 1977 (Lynnes & Lay, 1988; Gusman et al., 2009) generating a tsunami with 6 m wave heights observed in Western Australia (Goff & Chague-Goff, 2014). Source models for the 1977 Sumba event suggest ruptures could have extended from depths of 50 km to the surface, given total rupture widths of ~70 km based on a 45° dip (Lynnes & Lay, 1988; Gusman et al., 2009). Seismic reflection profiles reported by Saqab et al. (2017) suggest that active normal faulting also occurs within the Australian continental crust to the south of the Timor Trough. Multi-beam bathymetry over the Java Trench shows numerous surface features in the oceanic Australian plate that are interpreted as normal faults due to plate bending (Kopp et al., 2006).

Although Satake and Tanioka (1999) argue that outer-rise events should be included in tsunami hazard assessments, it appears in practice this is rarely done, and standard methods do not exist for characterising maximum magnitudes and recurrence rates for outer-rise events. Burbidge et al. (2008a) include a normal fault source near the location of the 1977 Sumba earthquake with alternative maximum magnitudes of 8.5 and 9.0, but do not consider outer-rise events elsewhere. Sleep (2012) uses plate kinematics to argue that the rate of moment release for outer-rise events on a particular part of the Japan trench should be 0.45% that of the corresponding megathrust. This is in part based on an assumed maximum seismogenic depth of 30 km, which is shallower than sources models for the Sumba earthquake, with maximum depths of 50 km (Gusman et al., 2009; Lynnes & Lay, 1988), and the 1933 Sanriku earthquake, with a maximum depth of 70 km (Kanamori, 1971). Our analysis of the GCMT catalogue shows large variations in the ratio of the rate of outer-rise to megathrust events (Davies & Griffin, 2018). Maximum magnitudes are highly uncertain; the largest recorded outer-rise event is the Mw 8.5 1933 Sanriku earthquake (Okal et al., 2016). However, magnitudes could presumably be at least as high as the maximum observed magnitude to have occurred within oceanic lithosphere (i.e. the Mw 8.6 April 11 2012 Wharton Basin Earthquake).

Outer-rise source models are included for the major subduction zones surrounding Australia: the Sunda Arc, Timor Trough, Solomons Arc, New Hebrides Arc and Tonga-Kermadec Arc. For the Puysegur Subduction Zone we only include an outer-rise source near the main trench, and don’t extend it further north (i.e. towards the Fiordland segment of the subduction zone) due to the highly oblique nature of subduction here (Hayes et al., 2009). The surface traces of the outer-rise sources were determined by taking the surface trace of the megathrust (i.e. the trench) and moving this slightly seaward (on the order of ~10 km). Dips of 45° and maximum depths of 50 km are assumed based on source models for the 1977 Sumba earthquake (Lynnes & Lay, 1988; Gusman et al., 2009).
3.5 Accompanying data files and summary of fault sources

The fault sources discussed in Section 3 are accompanied by shapefiles containing a base level parameterisation. These shapefiles give the geometry of the surface trace of the fault and contain a series of attributes providing information on fault geometry and slip-rate, as described in Table 1. Further schematisation of these sources is undertaken to prepare the PTHA18 and NSHA18 input files. This schematisation includes excluding some fault sources from the analysis that were not considered significant for tsunami and/or earthquake hazard assessment in Australia. Table 2 shows which fault sources presented in this report were included in the final PTHA18 and NSHA18 fault source models.

### Table 1: Description of fields provided in accompanying shapefiles.

<table>
<thead>
<tr>
<th>Field name</th>
<th>Description</th>
<th>Present in all files</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class</td>
<td>Class of fault type, one of ‘Thrust’, ‘Megathrust’, ‘Normal’ or ‘Strike-slip’</td>
<td>Yes</td>
</tr>
<tr>
<td>Concavity</td>
<td>Whether the fault interface is a concave ‘Up’, ‘Down’ or a ‘Linear’ plane</td>
<td>Yes</td>
</tr>
<tr>
<td>Dip_0</td>
<td>Dip estimated at the surface trace (degrees). If no other dip values are</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>given and concavity is ‘Linear’, then this value applies for the whole</td>
<td></td>
</tr>
<tr>
<td></td>
<td>fault.</td>
<td></td>
</tr>
<tr>
<td>Dip_&lt;depth&gt;</td>
<td>Dip estimated at the indicated depth (degrees). This value is used to</td>
<td>Most</td>
</tr>
<tr>
<td></td>
<td>construct non-linear (Concave up or down) models of the fault interface</td>
<td></td>
</tr>
<tr>
<td>Azimuth</td>
<td>Direction of the relative motion across the fault, measured in degrees</td>
<td>Most</td>
</tr>
<tr>
<td></td>
<td>clockwise from north</td>
<td></td>
</tr>
<tr>
<td>Sliprate_v</td>
<td>Magnitude of the relative motion across the fault, measure in mm/yr</td>
<td>Most</td>
</tr>
<tr>
<td>Sliprate</td>
<td>Magnitude of relative motion in a direction normal to the fault trace</td>
<td>Only provided if slip-rate is estimated without an estimate of the slip</td>
</tr>
<tr>
<td></td>
<td></td>
<td>azimuth</td>
</tr>
<tr>
<td>Max_depth</td>
<td>Estimated maximum depth of the seismogenic zone (km)</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Table 2: Summary of fault sources and whether they were included in the PTHA18 and NSHA18 source models.

<table>
<thead>
<tr>
<th>Fault source</th>
<th>Included in PTHA18 source model</th>
<th>Included in NSHA18 source model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sangihe Thrust</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Sangihe Backthrust</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Halmahera Forearc Thrust</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Cotabato Trench</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>North Sulawesi (Minahassa) Trench</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Parigi Fault</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Malino Fault</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Tolo Thrust</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Makassar Thrust</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Banda Detachment</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Flores Thrust</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Timor Trough</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Semau Fault</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Tanimbar Trough</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Aru Trough</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Seram Thrust</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Manokwari Trench</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>New Guinea Trench</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Manus Trench</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Mussau Trench</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Trobriand Trough</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Moresby (Aure) Trough</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Westland Faults</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Puysegur Trench</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>North Macquarie Ridge</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Hjort Trench</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>
4 Plate boundary and continental margin seismic source characterisation for NSHA18

Earthquakes to the north of Australia in the eastern Indonesia and Papua New Guinea regions have the potential to generate significant shaking in northern Australia. This has particular significance for Darwin, with several large earthquakes several hundred kilometres away in the Banda Sea having caused minor ground shaking related damage in Darwin over the historical period (Hearn & Webb, 1984; McCue, 2013). For plate boundary sources, the expert elicitation panel for NSHA18 recommended ground motions be considered for source to site distances of up to 800 km (Griffin et al., 2018). In this section active tectonic earthquake models within 800 km of onshore Australian territory are considered, excluding remote territories such as Christmas and Macquarie Islands, which will be treated in subsequent studies.

Major submarine fault systems are modelled using fault source models. Geometries and earthquake magnitude-frequency distributions are the same as those used for PTHA18. To ensure complete spatial coverage, area source models are defined for regions not covered by the major fault sources. Shallow area source zones are adapted and simplified from the 2017 Indonesian national seismic hazard assessment’s source model for eastern Indonesia (Irsyam et al. 2017; Section 4.1); seismic source models for PNG are taken from Ghasemi et al.’s (2016) national seismic hazard assessment for PNG with minor modifications (Section 4.2); and deep sources for intraslab earthquakes are schematized (Section 4.3).

For NSHA18, a panel of experts was used to define various uncertain model parameters through a structured expert elicitation process (Griffin et al., 2018). This panel recommended ground motions be calculated for source to site distances of up to 400 km for cratonic, non-cratonic and extended tectonic region types. The seismic source model for NSHA18 is composed of a number of different seismic source models for continental Australia, each with slightly different spatial extents, many of which do not extend their source zonation to a distance of 400 km offshore. Therefore sources for the Australian extended and oceanic margins are added (Section 4.4), and then individually stitched to each Australian seismic source model used in NSHA18 to ensure each model had complete coverage without any overlaps. Similarly, plate boundary sources to the north of Australia also need to be stitched to each source model. This stitching process is described in Section 4.5.

While this section describes the geometry of the seismic source models, the earthquake catalogue and methodology used to calculate recurrence statistics is described in the NSHA18 final report (Allen et al., 2018). Full parameterisation of the sources can be found in the NSHA18 Github repository for:

1. Area source models for plate boundary regions

2. Fault source models for plate boundary regions
   https://github.com/GeoscienceAustralia/NSHA2018/tree/master/source_models/banda; and

3. Area source models for continental margin and oceanic regions, stitched to the neotectonic domains model (for example)
4.1 Indonesian shallow crustal sources

Shallow crustal area source zones for the Indonesian region are adapted and simplified from the Indonesian PSHA (Irsyam et al., 2017), with some guidance taken from Badan Geologi’s models for Papua and West Papua (Omang et al., 2011; Sulaeman & Cipta, 2012). The Indonesian PSHA has a detailed fault source model that includes 250 individual fault segments; given the large source to site distances for Australian hazard, it is not considered necessary to implement this model at this level of detail. Instead, source zones are drawn encompassing the main fault zones defined by Irsyam et al. 2017, with guidance taken from the source zonation in Badan Geologi’s Papua and West Papua models (Omang et al., 2011; Sulaeman & Cipta, 2012). Maximum magnitude and fault geometry parameters for the zone are, in general, taken from Irsyam et al.’s (2017) parameterisation of the largest crustal fault contained in the zone, along with some reference to GCMT focal mechanisms. Shallow crustal area sources, and included fault sources, are shown in Figure 4. All values of maximum magnitude referred to below are expressed in terms of moment magnitude, $M_W$.

4.1.1 Tarera-Aiduna Fault System

The Tarera-Aiduna Fault System (TAFS) accommodates a significant component of the oblique motion between the Australian and Pacific Plates, linking the Wapengo Fault System, Aru Trough and Seram Thrust. A maximum magnitude of 7.8 is taken from the fault source in the Indonesian PSHA, which extends across the majority of the source zone. Following the Indonesian PSHA, the motion is strike-slip and our simplified model has a strike of 78°.

4.1.2 Wapoga

The strike-slip Wapoga Fault dominates this source zone. It has an average strike of 42° and a maximum magnitude of 7.9 is taken from the Indonesia PSHA.

4.1.3 Wandamen-Ransiki Fault Zone

This Wandamen-Ransiki Fault Zone (WRFZ) envelops both the Wandamen and Ransiki Faults; in the Indonesian PSHA fault source model there are a number of strands to the Wandaman Fault. The largest maximum magnitude is 7.2 for the Ransiki Fault. We model this zone as vertical strike-slip faulting along a strike of 160°; this is more consistent with the Ransiki fault, and we note that normal faulting occurs within the Wandaman Fault Zone.

4.1.4 Lengguru

The maximum magnitude of this zone is 7.0 based on the largest contained fault in the Indonesian PSHA (Wandamen-Kaimana). We model this zone as normal faulting based on this fault and nearby GCMT mechanisms, although thrust and strike-slip faults also occur in this zone. The zone is extended to form the NW boundary of the source model.

4.1.5 Cendrawasih

This zone contains the Cendrawasih Thrust, with parameters taken from this fault. This zone has a maximum magnitude of 7.6, and earthquakes are modelled as thrust events with a strike of 50° and dip of 40°.
4.1.6 Waropen

The Indonesian PSHA does not contain any mapped faults within this zone. For the purposes of NSHA18, we assume a maximum magnitude of 7.8 and model thrust faults striking at 97°, parallel to range fronts. We consider it most likely that strike-slip faulting occurs in the north of the zone.

4.1.7 Nusa Tenggara Shallow

A number of crustal faults are mapped within this source, which is bounded by the Flores-Wetar Thrust to the north and the Sunda Arc and Timor Trough to the south. The largest fault intersecting the zone is the strike-slip Semau Fault, from which representative parameters are taken with a maximum magnitude of 8.0 and strike of 10°.

4.1.8 Banda Sea

This zone encompasses the exposed footwall of the Banda Detachment. Although the main Banda Detachment is modelled as a fault source, it is assumed that normal faulting earthquakes could also occur within the footwall crust, and therefore we model this zone with normal faults dipping to west and striking 225°. A maximum magnitude of 8.0 is assumed.

4.1.9 West Banda Sea

This zone encompasses a broad region of the Banda Sea west of the Banda Detachment. The only mapped fault is the South Buru Fault, which is modelled as a thrust fault in the Indonesian PSHA. Focal mechanisms in the north (near Seram) and south (near Wetar Thrust) also show thrust faulting mechanisms, however in this tectonically complicated and poorly understand region all mechanisms could be possible. We assume a maximum magnitude of 8.0 and model thrust faults with strike 90° and dip 30°.

4.1.10 Tanimbar

For this source zone we model thrust faults striking 225° with a maximum magnitude of 8.0, based on the Tanimbar Thrust fault source in the Indonesian PSHA. As discussed above, these faults may more likely be thrust faults re-activated as normal faults; however for the purposes of modelling far-field ground motions for PSHA, the sense of faulting is not significant.
Figure 4: Shallow area source zones and fault sources for the eastern Indonesia region. Fault sources included in the NSHA18 model are labelled in italics, area sources zones labelled using plain text. Source models are overlain by focal mechanisms from the GCMT catalogue for earthquakes with magnitude > 6.0 and depth < 40.0 km. Abbreviations are: BTFZ – Bewani-Torricelli Fault Zone; MTB – Mamberamo Thrust Belt; PFTB – Papuan Fold-Thrust Belt; PFTB-FP – Papuan Fold-Thrust Belt – Fly Platform Transition; TAFS – Tarera-Aiduna Fault System; WRFZ – Wandamen-Ransiki Fault Zone.
4.2 PNG shallow crustal sources

Source zones for PNG, and some surrounding regions including parts of the Indonesian province of Papua, are taken directly from the PNG national seismic hazard assessment developed by Ghasemi et al. (2016). Minor adjustments to source zone boundaries are made in order to stitch with sources in Indonesian Papua, and to allow inclusion of the Moresby Trough as a fault source model. Note that unlike the other major submarine faults, we model the New Britain Trench as an area source, rather than a fault source model taken from PTHA18. This is because there are significant changes in geometry and slip rate along this fault as included in PTHA18 (Figure 2), which are not easily modelled with OpenQuake software (Pagani et al., 2014). Furthermore, we only require one segment of the structure for NSHA18, as the remainder is beyond the maximum cut-off distance for calculating ground motions.

Figure 5: Shallow area source zones and fault sources for the Papua New Guinea region. Fault sources included in the NSHA18 model are labelled in italics, area sources zones labelled using plain text. Source models are overlain by focal mechanisms from the GCMT catalogue for earthquakes with magnitude > 6.0 and depth < 40.0 km. Abbreviations are: BSSL – Bismarck Sea Seismic Lineament; BTFZ – Bewani-Torricelli Fault Zone; MTB – Mamberamo Thrust Belt; PFTB – Papuan Fold-Thrust Belt; PFTB-FP – Papuan Fold-Thrust Belt – Fly Platform Transition.
4.3 Intraslab sources

Earthquakes occurring within subducted oceanic slabs related to the Sunda-Banda Arc and the North Papua Subduction Zone are significant for seismic hazard in Australia. In particular, ground motions generated by earthquakes within the eastern Banda Arc slab propagate efficiently through the crust to northern Australia (Fishwick et al. 2005; Kennett & Abdullah, 2011; Wei et al. 2017), and have historically caused damage (McCue, 2013).

4.3.1 Indonesia

The Sunda-Banda Slab curves in an arc formed by subduction rollback of the Banda Arc into an embayment of the Australian continent that began ~15 Ma (Spakman & Hall, 2010; Pownall et al., 2016). Tight folding of the slab may be related to localised high rates of intermediate depth seismicity (Spakman & Hall, 2010), most pronounced to the north-east of Timor.

The geometry of the subducted slab was approximated by area source zones stepped in 100 km depth increments from 40 – 600 km depth. Definition of these zones was based on contours from the Slab 1.0 model (Hayes et al. 2012; only available for the Sunda Arc) and earthquake focal depths from the GCMT and ISC-GEM catalogues. For the shallower intraslab sources (40 – 400 km depth) the subducted Banda Slab is split spatially into Nusa Tenggara, Banda, Timor and Seram zones. Some of these zones did not have a sufficient number of earthquakes to robustly calculate recurrence statistics. Therefore earthquakes from all intraslab zones from 40 – 400 km depth were aggregated for calculation of recurrence statistics, with the exception of the Banda zones as these zones have a higher seismicity rate. Area-normalised recurrence rates were then applied to each individual zone, as described in more detail in Allen et al. (2018). Seismicity rates decrease further at depths greater than 400 km, and therefore we model two deeper zones (400-500 and 500-600 km) for the entire Banda Sea region. Recurrence statistics are calculated from aggregated seismicity from these two zones, with area-normalised rates again applied to each zone.
4.3.2 PNG

For PNG, we take the intraslab source model developed by Ghasemi et al. (2016), shown in Figure 7. These sources range from a depth of 40 km to 180 or 200 km, consistent with the relatively shallower depth of the Benioff zone of the North Papua Subduction Zone compared with the Banda Slab. We exclude their New Britain Deep intraslab source zone, as there are no earthquakes in the ISC-GEM catalogue that pass completeness in this zone; furthermore, as this deep source zone is located seaward of the New Britain Trench, we do not expect the presence of a subducted slab. We speculate that the intermediate depth earthquakes that fall within this zone in Ghasemi et al.’s (2016) catalogue may be poorly located.
4.3.3 Intraslab parameterisation

For all intraslab source models we apply a maximum magnitude of 8.3, commensurate with the largest intraslab earthquake recorded globally (the 1938 Banda Sea event; Okal and Raymond 2003). Applying this to the PNG source means we are adjusting maximum magnitudes provided by Ghasemi et al. 2016 up or down, as their maximum magnitudes for intraslab sources range from 8.0-8.5. Making this adjustment provides consistency between all intraslab source models, which are inherently difficult to parameterise given our lack of knowledge of within-slab seismogenic structures relative to shallow sources.

4.4 Extended margin and oceanic sources

The NSHA18 expert elicitation panel recommended calculating ground motion for extended margin sources to a distance of 400 km (Griffin et al., 2018). However the majority of the seismic source models contributed to NSHA18 do not have full spatial coverage to a distance of 400 km from the Australian coastline. Although in general seismicity in these regions is sparse, in order to ensure completeness of the hazard assessment additional source zones were added to the Australian seismic source models, covering a distance of 500 km from the mainland and Tasmanian coastlines. The new
source zones were based on fundamental tectonic region types (extended crust, oceanic crust) sourced from the Neotectonic Domains Model (Clark et al., 2012), and the Australian Geological Provinces Database (Raymond, 2018) for regions extending beyond the extent of the Domains model. Figure 8 shows the additional offshore sources as integrated with the neotectonic domains source model. As some of these zones contained an insufficient number of earthquakes to calculate recurrence statistics robustly, earthquakes from neighbouring source zones were aggregated for the purpose of calculating recurrence statistics, in some cases mixing extended and oceanic tectonic region types.

Figure 8: Source zonation for the modified neotectonic domains model, showing the addition of continental margin and oceanic sources (coloured in shades of blue). The northernmost source models are extended to meet the plate boundary sources, ensuring complete coverage. Abbreviations are: MLFR – Mount Lofty and Flinders Ranges; OGS Basins – Otway, Gippsland and Sorel Basins.

4.5 Stitching of plate boundary model to Australian source models

The source model for regions north of Australia was merged with the source models for Australia to form multiple stitched models. The Australian models were given precedence where spatial overlap between the two source models was present. Changes to the source zones for regions north of
Australia as a result of clipping overlapping areas occasionally created source zones that were too small to robustly calculate recurrence statistics. In these cases, these source zones were merged into the neighbouring source zones from the Australian models.
5 Summary

This report outlines the rationale and evidence supporting the revision of earthquake source models for plate boundary regions to the north and east of Australia to underpin the 2018 Australian PTHA and NSHA, and to support tsunami hazard assessment in Indonesia. The new model draws on recent literature that improves our understanding of the active tectonics of the region and includes a number of fault sources not considered in previous PTHA. The new model includes non-subduction tectonic sources with the potential to generate tsunami and/or ground shaking hazard impacting Australia that were not fully considered in previous hazard assessments, including the Banda Detachment, Aru Trough, Moresby Trough and Macquarie Ridge. For the first time, outer-rise source models for all major subduction zones are also considered in a systematic manner.

For seismic hazard assessment, area source models are developed for active tectonic regions based on simplifications of recent updates to national seismic hazard assessments for Indonesia (Irsyam et al., 2017) and PNG (Ghasemi et al., 2016). Area source models are also developed for continental and oceanic margins of the Australian continent, and a model with complete and non-overlapping coverage developed.

The tectonic complexity of the region means we can expect the interpretations presented herein to change as future studies are undertaken. Therefore future tsunami and earthquake hazard assessments undertaken for the region should consider revision of the earthquake sources models presented in this study.
6 Acknowledgements

The authors are grateful to Masyhur Irsyam for sharing the earthquake source model for the 2017 Indonesian PSHA. The authors thank Matthew Gale for GIS assistance preparing the Australian continental and oceanic margin sources and stitching them to the continental and active region models. Discussions with Ignatius Ryan Pranantyo and Phil Cummins assisted interpretation of source models in eastern Indonesia. Hadi Ghasemi assisted with interpretation of the 2014 PNG seismic hazard assessment. Trevor Allen and Dan Clark provided advice on development of continental margin and intraslab sources. Trevor Allen, Phil Cummins, Jane Sexton and Leesa Carson provided helpful reviews of the final report.
References


Earthquake sources of the Australian plate margin


