Seismic Source Model Development for Australia's Northwest Shelf

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Abstract

A seismic source model for use in Probabilistic Seismic Hazard Analyses (PSHA) has been developed for Australia's North West Shelf (NWS). The model incorporates active tectonic elements of the Sunda Arc subduction zone, Banda Arc collision zone, as well as the rifted margin and stable continental regions of northwestern Australia. The model includes dipping planar fault zones that represent subduction zone sources and areal sources that represent seismotectonic provinces. The source zonation includes 13 subduction zone sources and 40 shallow crustal sources. Approaches used to develop geometry, depth, style of faulting, segmentation, magnitude, slip rate, and recurrence parameter values are discussed. The approaches allow use of alternative interpretations of rupture length, hypocentral depth, slip rate, and seismic efficiency along with multiple empirical relationships among fault length, area and magnitude to incorporate epistemic uncertainty in source parameter values.

The Sunda Arc subduction zone has the potential to generate great earthquakes of M_w 8.3 to 9.1 with recurrence intervals of roughly 330 to 950 years and thus will contribute significantly to the hazard along the northwestern NWS. The Banda collision zone also has the potential to produce large earthquakes, in the M_w 7.7 to 8.4 range, with recurrence intervals of ~300 to 1,500 years, and thus will contribute significantly to the hazard along the Sahul Shelf, Timor Sea and northern NWS. For the southern NWS, local fault sources have the potential to produce earthquakes of M_w 7.0 to 7.5 (e.g. M_w 7.3 Meeberrie earthquake) and thus will dominate the hazard compared to the distant subduction zone sources.

Keywords: Sunda Arc, North West Shelf, active tectonics, stable continental region earthquakes, seismic source model, seismic hazard analysis

1.0 INTRODUCTION

Probabilistic seismic hazard analysis (PSHA) techniques are now routinely used in computing ground motion hazards for engineered facilities. PSHA can be used to assess the level of earthquake strong ground shaking that might be expected during a specified period of time for a particular site or area, and to develop the design spectra for use in facility engineering. Performing a PSHA requires two basic inputs that describe earthquake sources and the transmission of seismic energy through the earth's crust. These two basic components of the PSHA are referred to as the seismic source model and the ground motion attenuation model. The seismic source model defines the location and geometry of seismic sources and specifies the maximum earthquake magnitude, activity rates, and rupture characteristics for seismic sources in a model region (Hengesh and Lettis, 2005). The ground-motion attenuation model describes how ground motions diminish with distance away from a seismic source (see for example Somerville et al., 2009). This paper describes development of a seismic source model for Australia's North West Shelf (NWS).

Previous published seismic source models developed for the region have followed political boundaries and therefore do not provide a complete description of earthquake sources that affect the NWS. For example, the AUS 5 model of Brown and Gibson (2004) provides a detailed zonation of shallow crustal area source zones for the entire Australian continent, but does not include source zones for the Sunda and Banda arc segments of the plate boundary (described below). Similarly, the most recent update of the Indonesian Building Code (Irsyam et al., 2010) uses a source model that includes the main plate boundary features, but does not include any sources within Australia. The source zonation presented below is based on a detailed analysis of geological, seismological, tectonic, and geodetic data and incorporates active plate boundary sources, as well as sources along the NWS and within the Australian craton. The approach discussed below for developing the parameter values for use in PSHA allows incorporation of alternative interpretations of rupture length, hypocentral depth, slip rate, and seismic efficiency to incorporate epistemic uncertainty in the hazard analysis.

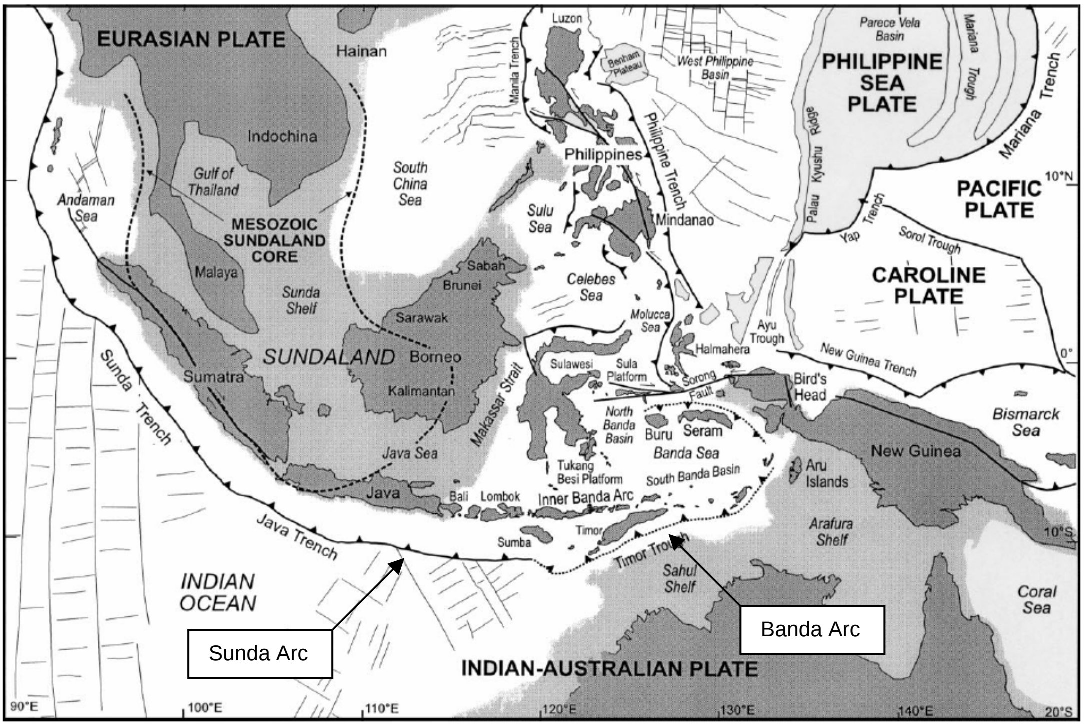


Figure 1. Regional tectonic setting of Southeast Asia and northern Australia. The light shaded areas are continental shelves of Eurasia and Australia. From Hall and Wilson (2000).

2.0 REGIONAL TECTONIC SETTING

The northwest Australian continental margin records a history of over 725 million years and includes development of foreland basins, intra-cratonic rifts, rifted-margin, passive margin, and now a collisional margin. The northern margin of the Australian plate is characterized by active plate boundary subduction and collisional processes (Figure 1), and the western margin is characterized by passive "Atlantic-type" processes.

The northwestern margin of the Australian Plate is involved in a complex collision with the Sunda Shelf part of the Eurasian plate and marginal seas of the Indonesia region (Figure 1; Hall and Wilson, 2000). The Australian plate is moving along an azimuth of between 011° and 015° and is converging with the Sunda Arc subduction zone and the Banda Arc collision zone at a rate of 56 to 72 mm/yr relative to a fixed Sunda Shelf reference frame (Figure 1; Simons et al., 2007).

The northwestern part of the Australian Plate consists of two main parts including Australian continental crust and oceanic crust of the Indian Ocean, and the differences in crustal type control the nature of processes occurring along the plate boundary. In the past, subduction has occurred along the entire Sunda and Banda plate boundary, but now is limited to that part of the plate boundary where oceanic crust of the Indian Ocean is colliding with the trench (Silver et al., 1983). Subduction extends from the Andaman Islands in the northwest to approximately 120-121° east longitude near the island of Timor. East of this location, the Indian Ocean crust already has been consumed, subduction has ceased, and fragments of former island arcs are being accreted to the Australian Plate (Keep et al., 2003). The collision of Australian continental crust with the southern Banda Arc has caused profound changes in the style of deformation along the plate boundary including reduction or cessation of north-directed subduction, accretion of the former island arc, and reversal of subduction polarity.

The collision of Australian continental crust with the southern Banda Arc also is causing deformation of northern and northwestern Australia including regional tectonic warping (Hengesh et al., 2010), reactivation of older rift-related structures (Keep et al., 2000), and surface faulting (Clark et al., 2006). This deformation has caused the occurrence of large magnitude earthquakes including the 1941 M_w 7.1 Meeberrie earthquake. Therefore, seismogenic sources along the plate boundary and within the Australian plate need to be incorporated in the seismic source model for the NWS.

3.0 SEISMIC SOURCE CHARACTERIZATION

Ground motion analyses for projects on the NWS may require consideration of earthquake sources in the Sunda Arc subduction zone, Banda Arc collision zone, reactivated rift related structures along the northwestern Australia continental margin, and the stable continental regions within the interior. These four tectonic provinces have been subdivided into the 53 distinct seismic source zones that model sources of earthquakes along the subduction zone and within the shallow crust (Figure 2).

3.1 Subduction Zone Sources

The seismic source model includes seven subduction zone plate interface segments (shown in red on Figure 2). The geometries of the subduction zone segments are based on changes in orientation of the Sunda and Banda arcs, the change in crustal type from oceanic to continental (Silver, 1983), the presence of asperities along the plate boundary (Keep et al., 2003), and the presence of discrete crustal blocks with unique motion vectors (Bock et al., 2003; Nugroho et al., 2009). Four subduction zone plate interface segments are defined along the Java trench, two along the Timor trough, and one along the Aru trough.

Subduction zone sources are characterised by three separate types of earthquake occurrence models. These include: (1) characteristic earthquakes (i.e. M_w>8) caused by thrust motion on the dipping plate interface between depths of about 10 to 45 km;

(2) distributed earthquakes with magnitudes less than the characteristic events originating along the plate interface and within the descending slab between depths of about 10 and 45 km; and (3), deep earthquakes (depths greater than ~45 km) referred to as "intraplate" events that occur within the subducted oceanic slab down dip of the plate interface.

The first two types of sources are combined to form a truncated exponential earthquake recurrence model that includes both large magnitude characteristic earthquakes and smaller intracycle events on the plate interface zone. The intraplate source is modeled with a Gutenberg-Richter-type exponential recurrence model.

Segmentation and Maximum Earthquake Magnitude Distributions

A maximum earthquake magnitude distribution (M_{max}) is defined for each plate interface segment based on a range of fault rupture scenarios (characteristic earthquakes). A range of potential M_{max} events is developed so that the seismic source model represents the uncertainty in available data and natural variability in the rupture process. For subduction zone sources, maximum earthquake magnitudes can be estimated using the length-magnitude relationships of Dorbath et al. (1990), and area-magnitude relationships of Geomatrix (1993), and Wyss (1979).

Factors that should be considered in the analysis of maximum magnitudes include: (a) the minimum size of the rupture area based on the maximum historical earthquake for each segment; (b) uncertainties in potential length and/or width of a rupture area; (c) presence of physical features on the subducting plate (i.e. Roo Rise and Scott Plateau) or overriding plate (Sumba continental sliver) that could act as rupture segmentation points; and (d) maximum possible rupture dimensions for events larger than historical maximums. The depth limits for ruptures on the plate interface can be constrained by the approximate limits of the 100° to 350°C isotherms (lines of constant temperature), within which most large magnitude subduction zone earthquakes occur (Peacock and Hyndman, 1999). An example of the parameter values used to calculate M_{max} are shown for the East Java segment on Table 1.

Table 1. Example single segment source parameter values used to estimate Mmax for plate interface zones.

Estimated Dip of Plate Interface			Max Rupture Depth (km)			Down-Dip Rupture Width (km)			Estimated Rupture Length (km)			Rupture Area (km^2)		
Min	Mid	Max	Min	Mid	Max	Min	Mid	Max	Min	Mid	Max	Min	Mid	Max
21	22.5	24	35	40	45	86	105	126	230	335	440	19792	35016	55250

M_w (Length) (Dorbath et al., 1990)			M_w (Area) Geomatrix (1993)			M_w (Area) (Wyss, 1979)		
Min	Mid	Max	Min	Mid	Max	Min	Mid	Max
8.3	8.5	8.7	8.2	8.4	8.5	8.3	8.5	8.7

Given the limited available paleoseismic data for the Java and Timor segments it is necessary to consider the possibility of great earthquakes involving multiple segment ruptures. The length and area combinations for one, two and three segment ruptures, and the three empirical relationships used to estimate magnitudes, result in M_{max} values that range from M_w 8.3 to 9.1 for the Java Trench part of the subduction zone, and M_w 7.9 to 8.4 for the Timor trough. Four segment ruptures also can be considered, but the resulting magnitudes are considered by this author to be unrealistically large (e.g. M_w 9.4 to 9.8).

Slip Rate and Earthquake Recurrence

Fault slip rates are used to compute the recurrence of characteristic earthquakes on the plate interface segments. However, because no fault-specific slip rate data are available for the Java, Timor or Aru subduction zones it is necessary to use published geodetic data (Bock et al., 2003; Nugroho et al., 2009) that provide the total relative plate motion rate across the plate boundary. The total rate is corrected by assuming that only the plate-normal component of relative motion accumulates and ultimately is released during great earthquakes on the plate interface, while the plate margin parallel component of motion is partitioned onto shallow crustal sources (Sieh and Natawidjaja, 2000), such as structures within the Banda Sea (McCaffrey, 1989). Because of the obliquity of the plate motion azimuth relative to plate boundary structures, only part of the total relative plate velocity is accommodated on the interplate zones (Table 2).

Slip rates on plate interface segments also are corrected to account for the observation that in subduction zones worldwide, only a fraction of the measured motion produces elastic strain energy that is released by earthquakes. The proportion of strain accumulated on the plate interface relative to the total possible strain is described by the seismic coupling coefficient (Pacheco et al., 1993). The published seismic coupling coefficient for the Java segment of the Sunda Arc subduction zone is 1%, indicating that for every 100 meters of slip along the plate interface, only one meter is released seismically. McCaffrey (1996), however, indicates that there can be an order of magnitude or more uncertainty in these estimates.

Although the seismic coupling coefficient is a major source of uncertainty in final slip rate values, the lack of great earthquakes over the past several hundred years supports the interpretation that a large part of the strain across the plate boundary is released aseismically. Applying all of the relative motion between plates will result in an overly conservative assessment of fault slip and earthquake recurrence. This has the effect of artificially driving up hazard results.

The effective slip rates that should be used in hazard analyses account for both strain partitioning and seismic coupling. An example derivation of effective slip rates for the East Java interplate zone is presented in Table 2.

Table 2. Calculation of Effective Slip Rates for the Java Trench and Timor Trough Interplate Segments

Seismic Source Name	Plate Convergence Rate (mm/yr)			Obliquity (deg.)	Plate Normal Rate (mm/yr)			Seismic Coupling Coefficient	Effective Slip Rate (mm/yr)		
	Min	Mid	Max	Ave	Min	Mid	Max	Ave	Min	Mid	Max
East Java	63	69	75	13	57.5	65.3	73.1	0.2	11.5	13.1	14.6

Once effective slip rates are defined, earthquake recurrence intervals are estimated for the characteristic earthquakes associated with each single interplate segment or multiple segment rupture. Recurrence intervals are calculated by dividing the seismic moment (M_o) of each characteristic earthquake by moment rate, where moment is calculated directly from the relationship between M_o and M_w (Hanks and Kanamori,

1979) and moment rate is calculated as the product of effective slip rate, crustal rigidity, and rupture area of each characteristic earthquake. Table 3 summarises the calculated earthquake recurrence intervals for the example of the East Java segment.

Table 3. Summary of recurrence intervals for the East Java Segment

Name	Effective Slip Rate (mm/yr)	Moment Magnitude (Mw)	Recurrence (yrs)
East Java	12.3	8.2	222
	13.4	8.5	298
	14.6	8.7	432

3.2 Intraplate Source Zones

Six intraplate seismic source zones are included in the source model (shown in blue on Figure 2). The intraplate source zones model the occurrence of earthquakes within the subducted Indian Ocean slab below the depth of the plate interface. Magnitude estimates are based on recorded seismicity and examples of events from similar tectonic settings. The largest recorded intraplate earthquakes are typically on the order of M_w 7.75 to 8.3. The historical magnitude frequency distribution for intraplate source zones is determined for those events occurring within the volume of crust defined by the map projection of the intraplate zone and extending from the base of the shallow crust (e.g. 45 km) to the maximum depth of recorded earthquakes inferred to be associated with the subducted slab. Earthquake recurrence for subduction zone intraplate sources is modeled using a truncated exponential magnitude distribution.

3.3 Shallow Crustal Source Zones

The seismic source model for shallow crustal sources includes 40 areal zones that characterize the occurrence of shallow crustal earthquakes (Figure 2). Areal source zones represent regions with similar tectonic and seismological characteristics and are modeled as having uniform magnitude, recurrence and style of faulting parameter values. Shallow crustal source parameter values that are required for input to a PSHA include: (1) source location; (2) depth of earthquake occurrence; (3) style of faulting; (4) maximum earthquake magnitude (M_{max}) distributions; and (5) earthquake activity rates.

Definition of the areal source zones is based on examination of geomorphological characteristics, fault locations and kinematics, tectonic block boundaries and historical seismicity. The geometries of the aerial source zones on Figure 2 mimic the major tectonic trends of northwestern Australia and the Sunda and Banda arcs. The major features modeled include: (1) shallow crust above plate interface and intraplate zones (lying above the red and blue zones); (2) the outer arc rise/forearc region (purple zones); (3) oceanic crust (black zones); (4) areas of extended and modified continental crust (green zones); (5) the rift systems (green zones); and (6) stable continental regions of northwestern Australia (black zones).

The distribution of earthquakes with depth is incorporated into a hazard model by partitioning earthquake activity rates by depth. The depth intervals are assigned based on analysis of the depth distribution of earthquakes reported in the seismicity catalog for each zone. A common practice in PSHA's is to assign all seismicity to a unique depth (e.g. 10 or 15 km). However, for local seismic sources this approach can concentrate seismicity that occurs at deep crustal levels at a shallow depth, thus artificially reducing the source to site distance and increasing the hazard.

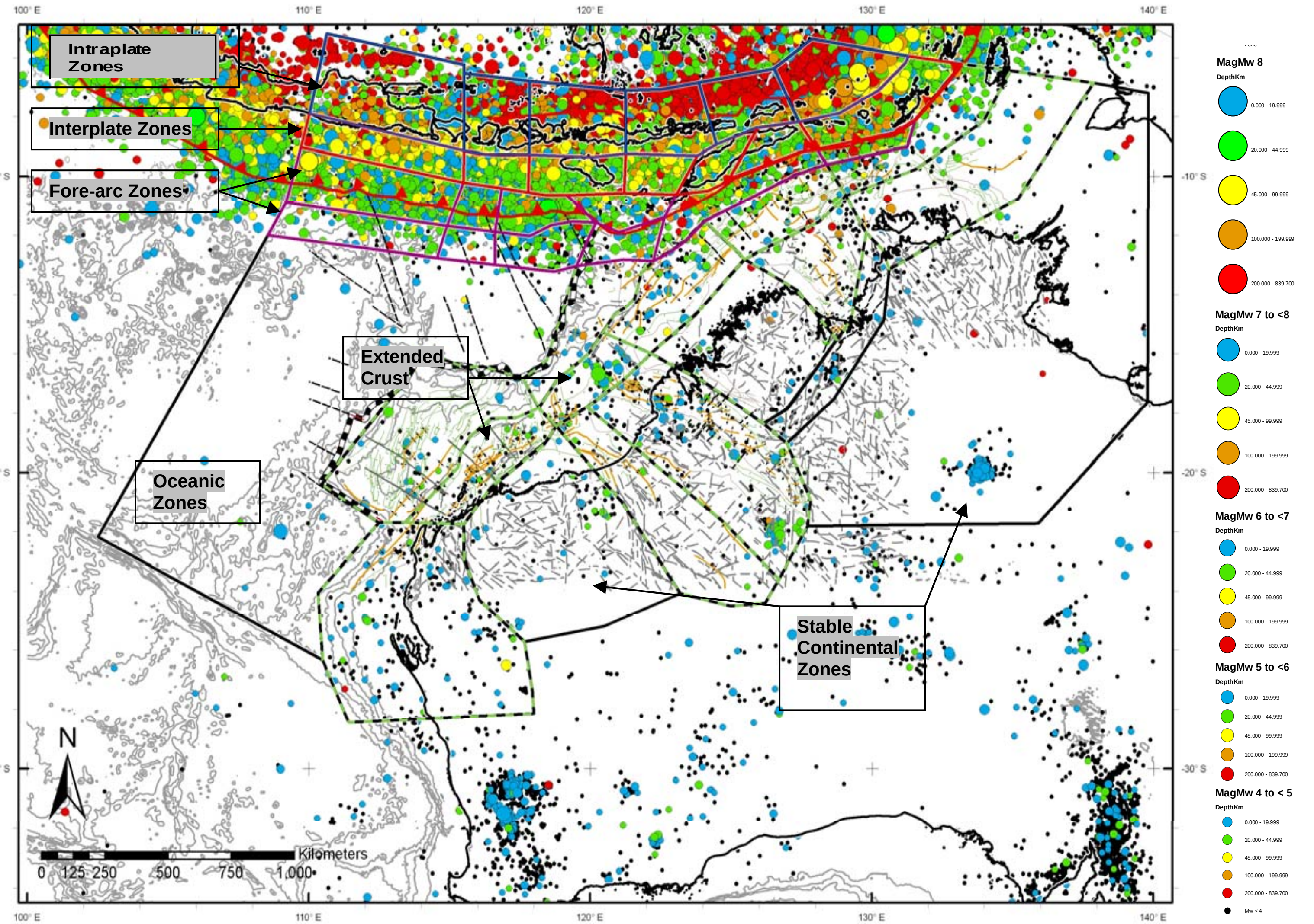
The M_{max} values associated with each zone are estimated based on the recorded historical maximum magnitudes, fault lengths, crustal thickness, and comparison to analogous tectonic features in other regions (Clark et al., 2010). For example, the global record of earthquake occurrence in stable continental regions indicates that larger earthquakes occur in areas underlain by extended continental crust (i.e. former rifted margins) than areas underlain by non-extended crust (Johnston et al., 1994; Shulte and Mooney, 2005). Higher relative magnitude distributions should therefore be assigned to areas of extended and modified continental crust than the non-extended stable continental regions of northwestern Australia. Areas of extended continental crust typically have M_{max} values in the range of M_w 7.0 to 7.5, but can be as high as M_w 7.7 (Wheeler, 2009). M_{max} values for stable continental regions are typically assigned values in the range of M_w 6.5 to 7.2. However, the occurrence of several earthquakes in of M_w 6.7 in Western Australia suggests that the minimum M_{max} value should not be lower than M_w 6.8.

The style of faulting inferred for each shallow crustal source zone is dependent on structural trends and the dominant regional stress pattern for that particular area. The regional stress patterns change from north to south across the model area. In the north, the regional stress pattern is dominated by northeast-southwest directed compression, while in the southern part of the model area the regional stress pattern is dominated by east-west compressive stress (Reverts et al., 2009). Therefore, although faults in the northern and southern parts of the model area may have similar orientations, the style of faulting likely to occur along those faults will vary depending on whether it is undergoing northeast-southwest compression, or east-west compression. Earthquake recurrence in areal source zones is modeled using a truncated exponential magnitude distribution.

4.0 DISCUSSION

The seismic source zonation presented on Figure 2 models the geometry of potential earthquake sources that could affect Australia's NWS. The source zonation includes 40 shallow crustal sources and 13 subduction zone sources that model the main seismotectonic provinces that have a significant influence on the location, style, and rates of earthquake occurrence along the northwestern Australia plate boundary. These include the: Sunda Arc subduction zone; Forearc Province; Banda Arc collision zone; Transitional Zone; Northwest Australia rifted margin and marginal basins, and Australian stable continental region.

The Sunda and Banda arcs have the potential to produce large to great magnitude (e.g. M_w 8 to 9+) earthquakes with recurrence intervals of several hundred to a few thousand years. These events would make a significant contribution to the hazard for sites within a few hundred kilometers of the trench/trough system. Although the southern NWS (Exmouth Plateau) is located at too great a distance for these earthquakes to significantly effect design ground motions for platform and pipeline systems, consideration needs to be given to the effect that distant large magnitude earthquakes have on design of specialized systems such as LNG tanks.



Polygons:
Blue = intraplate zones
Red = interplate zones
Purple = forearc/outer arc rise and transitional crust
Green = extended crust of rifted margins and basins
Black = non-extended crust and oceanic crust
Dashed lines illustrate common boundaries

Faults:
Red = Subduction/collision zone
Green = rift related structures
Tan = hinges and fold axis
Black = lineaments and minor faults in cratonic regions
Modified from AGSO (1994)

Bold dashed black and white line is the continent/oceanic terrane boundary.

Bathymetric contour interval = 1,000 metres

Figure 2. Seismic source zonation for the North West Shelf

The Forearc and Transitional Crust provinces also have the potential to produce large magnitude earthquakes (e.g. M_w 7.75 to 8.3). These sources are close to the northern margin of the NWS and therefore would make a significant contribution to the ground motion hazard in this area.

The parts of the NWS that follow the continental shelf encompass a series of late Paleozoic rifts and Middle to Late Mesozoic rifts and rifted margin structures that are today the focus of significant resource development activity. A number of these structures show evidence of Late Miocene to Recent reactivation and are potential sources of future seismic activity. Although the rates of earthquake activity along these older rift related structures are low compared to the plate boundary zone, large magnitude earthquakes (e.g. M_w 7.3 to 7.5) can occur. These events will control the hazard for areas along the continental shelf and along the Exmouth Plateau.

For projects on the northern part of the NWS, Sahul Shelf, and Timor Sea seismic source models should include parameters for both subduction zone sources and shallow crustal sources. However, seismic source models developed for projects on the southern part of the NWS (e.g. Carnarvon Basin), may not need to incorporate subduction zone sources due to the large source to site distances. Careful consideration needs to be given to the effect that large distant earthquakes may have on facility design, especially for specialized systems such as LNG storage tanks.

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