Characterization of seismic sources within northwestern Australia's newly reactivated transcurrent margin

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ABSTRACT: A new phase of tectonic reactivation is occurring along Australia's North West Shelf (NWS) due to reorganization of the northern plate boundary in the past 3.0 to 0.2 Ma. A 1,400 km long fault system deforms Pliocene to Recent deposits across the Browse, Roebuck, and Carnarvon basins, and aligns with a system of onshore Quaternary faults and folds that extend another 600 km to the Murchison region. The fault system has relatively higher rates of seismic activity than adjacent non-extended terranes, has produced the largest historical earthquake in Australia, (1941 M_L 7.1 Meeberrie event), and multiple M_w 6+ events. The very large 1906 M_S 7.8 offshore event also may be related to this tectonic reorganization. Seismicity is dominated by focal mechanisms consistent with dextral motion along northeast trending fault planes. The median estimate of horizontal slip rate across the zone is on the order of 3 mm yr^{-1}, barely in the range of geodetically detectable strain, but the geological record clearly shows the presence of a major fault system capable of producing earthquake in the range of ~M_w 7.5 to 8.0. Future seismic hazard assessments for facilities on the NWS and along the coastline of western Australia should incorporate fault sources that model the activity of these seismogenic sources.

1. INTRODUCTION

The Indo-Australian plate is migrating northward along an azimuth of 011° to 015° at a rate of 56 to 72 mm/yr relative to a fixed Sunda Shelf reference frame (Minster & Jordan, 1978; Tregoning, 2003; Bock et al., 2003; Nugroho et al., 2009) and is converging with marginal seas and continental fragments of southeast Asia along the Sunda Arc subduction zone and the Banda Tectonic Collision Zone (Fig. 1-1). The North West Shelf (NWS) part of Australia's western passive margin trends in a north-northeast direction until it is truncated by the northern plate boundary. The transition from Indian oceanic crust to Australian continental lithosphere profoundly changes the style of deformation along the northern plate boundary (Silver et al., 1983; McCaffrey, 1988; Audley-Charles, 2004, 2011; Harris et al., 2009; Fluery et al., 2009). There is northward directed subduction of Indian oceanic crust west of the Scott Plateau near 120°E longitude (Shulgin et al., 2009). However, east of this location the oceanic crust has been fully consumed and subduction along the Banda trench has ceased (Silver et al., 1983; McCaffrey, 1988; Hall, 2011; Harris, 1991, 2006; Audley-Charles, 2011). The former subduction zone has become blocked by Australian continental lithosphere and has evolved into a tectonic collision zone (TCZ) where the former accretionary prism has emerged along large scale nappe structures to form Timor and Sumba islands (Audley-Charles, 1975, 1985; Keep et al., 2003; Duffy et al., 2013) and the Suva-Rota ridge (Roosmawati and Harris, 2009; Rigg and Hall, 2011). There is now south directed thrusting of Timor relative to Australia across the Timor trough at a rate of 15 +/-8 mm/yr (Nugroho et al., 2009).

The termination of the Java subduction zone coincides with the former western rifted margin (extended crust) of Australia (Hengesh & Whitney, 2014). Changes in plate motion vectors across the transition zone from subduction to arc-continent collision have developed a right lateral shear couple that is reactivating faults along the extended margin (Whitney & Hengesh, this volume). The reactivated western margin of Australia is referred to as the Western Australia Shear Zone (WASZ), which comprises an offshore system of dextral transcurrent faults that extend 1,400 km from Ashmore Reef to the Cape Range, and then extends onshore another 600 km to the south-southeast (Fig. 1-1)

(Whitney & Hengesh, 2015a,b, Whitney et al., 2015a,b). This is a regionally significant, but low activity fault zone that has not been detected by regional geodetic analyses. This may be due to the fact that the geodetic analysis of the Australian continent relies on stations that are mostly located on the non-extended part of the crust (inset Fig. 1-1) inboard of the extended margin that formed during Mesozoic continental rifting. Therefore, the analyses of Tregoning (2003) and Leonard (2008) confirm the stability of the non-extended part of the continental lithosphere, but due to station locations cannot account for deformation occurring along the WASZ where rift-era structures are now being reactivated (Hengesh and Whitney, 2014). This zone of tectonic deformation occurs between the stable continental interior and oceanic basins and provides an example of intraplate deformation within the Indo-Australian plate.

In this paper we interpret 2D and 3D seismic data that document specific faults within the WASZ that extend across the Browse, Roebuck, and Carnarvon basins on Australia's NWS (Fig. 1-1). We then provide a summary of the source characteristics for several of the faults within the system to illustrate how these sources might influence future seismic hazard assessments.

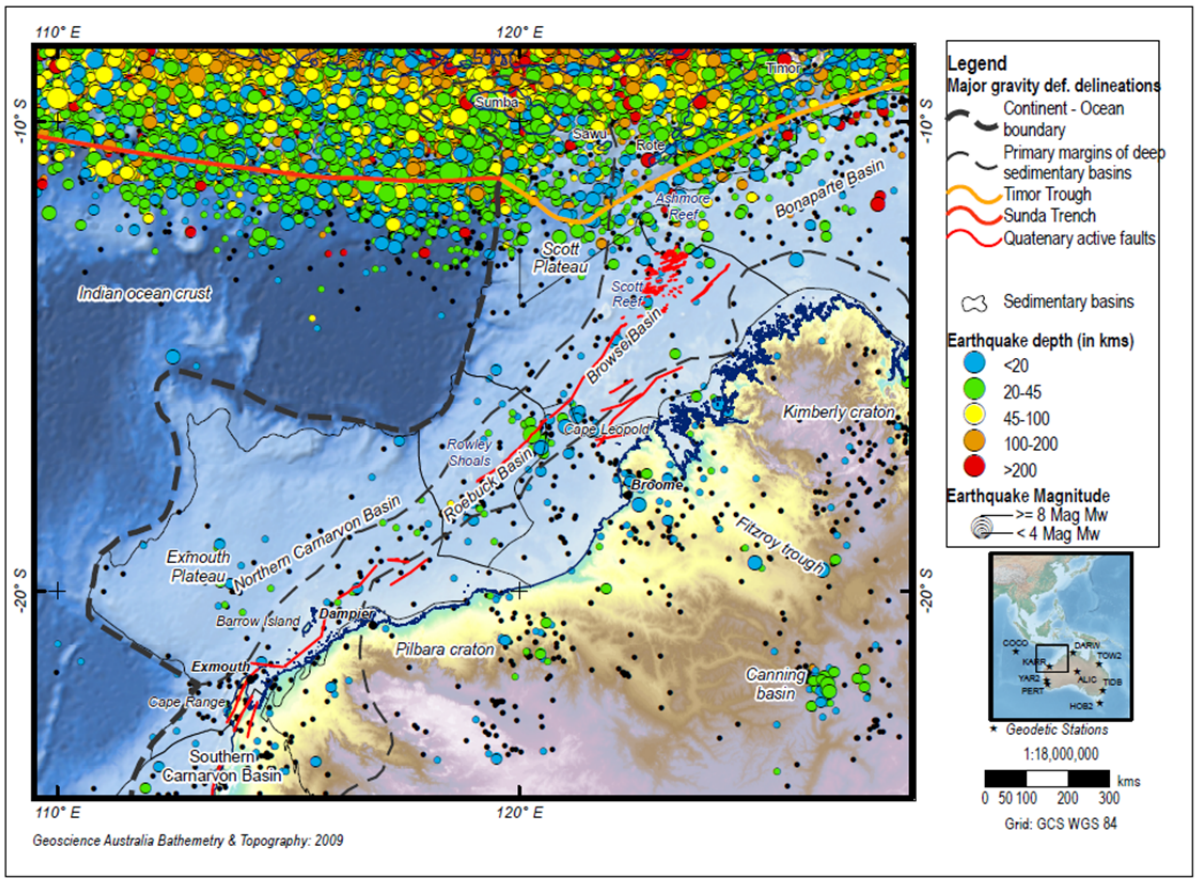

Figure 1-1. Regional map showing principal geological provinces and structural trends. Red faults form offshore part of the WASZ. For legibility, not all structures within the WASZ are shown. Inset shows geodetic station location used by Tregoning (2003) and Leonard (2008).

2. ACTIVE TECTONIC STRUCTURES WITHIN THE WESTERN AUSTRALIA SHEAR ZONE

We used the Geoscience Australia Browse Basin High Resolution (BBHR) 2D survey to provide broad coverage of Browse basin, North Browse 3D data to illustrate the more detailed characteristics of faulting from the base Pliocene and seafloor within Browse basin, and the 2014 Geoscience Australia data release (Cortese et al., 2014) for the Roebuck basin and Rowley Shoals area. We focus on the post-Pliocene period as it corresponds to the timing of the onset of collision along the Sumba,

Savu and Rote islands part of the northern plate boundary (Roosmawati and Harris, 2009) between 3.0 and 0.2 Ma and eliminates potential confusion with earlier Neogene reactivation (Keep et al., 2007) of rift era structures (Cathro and Karner, 2006). We discuss two examples of faulting: one fault zone that extends 800 km along the outer continental shelf from Ashmore Reef to Rowley Shoals; and a second fault zone that extends 400 km along the inner continental shelf from near the Dampier peninsula to the Cape Range (Fig. 1-1).

2.1 Outer Shelf Fault Zone

The Outer Shelf fault zone initiates in northern Browse Basin as a 50 km wide by 100 km long zone of N70°-80°E trending transtensional faults, which form a zone of horsts and grabens that deform the seafloor. These faults then connect to a 550 km long zone of N35°-50°E trending transpressive faults that extend from Scott Reef to Rowley Shoals, and which also deform the shallow subbottom sediments and the seafloor (Fig. 1-1). Seismic line BBHR-11 documents an approximately 32 km wide deformation zone that consists of two separate sub-parallel shear zones referred to as the Inner Basin North and Inner Basin South shear zones. The Inner Basin North shear zone is 6.3 km wide and the Inner Basin South shear zone is 8.3 km wide. These two shear zones are separated by a relatively undeformed block that is 9 km wide. There is an overall down-to-the-northwest sense of vertical deformation (Fig. 2-1).

The Outer Shelf fault zone is characterized by antiformally folded basement, as well as folded Mesozoic and Tertiary sections. The fault zone deforms the Pliocene and Quaternary stratigraphic interval and locally deforms the seafloor reflector (Fig. 2-1). As shown on this figure, the green horizon marks the stratigraphic position of the base of the undifferentiated Pliocene to Holocene interval defined by Simpson and Cooper (2008). The yellow horizon indicates the position of a late Quaternary to Holocene erosional unconformity near the top of the section (Simpson and Cooper, 2008).

The antiforms are overlain by the base Pliocene erosional unconformity, which is cross cut by faults that have produced 0.36 to 0.42 sec two way travel time (TWT) (288 to 336 m assuming 1600 m/sec shear wave velocity) of cumulative down-to-the-west vertical displacement of the unconformity. The faults extend upward through the section and have produced 0.26 sec TWT (~208 m) of cumulative down-to-the-west vertical displacement of the late Quaternary to Holocene erosional unconformity (Fig. 2-1). Displacements of the late Quaternary to Holocene erosional unconformity on individual fault strands are approximately 0.03 to 0.05 sec TWT (24 to 40 m).

2.2 Inner Shelf Fault Zone

A series of fault segments continue southward from offshore Cape Leopold on the north to offshore Dampier on the south (Fig. 1-1). A fault segment lies approximately 70 km northwest of Dampier peninsula along the trend of other Inner Shelf fault segments. The structure is 150 km long, 1.8 km wide, and trends in a N50°E direction. This fault segment (observed on line s136_136_24_mig_time, 6155.22) has produced 0.125 to 0.15 sec TWT (100 to 120 m) of down-to-the-west displacement of the base Pliocene horizon, and 0.03 to 0.05 sec TWT (24 to 40 m) of down-to-the-west displacement of an inferred Quaternary unconformity (Fig. 2-2). The seabed in not deformed, but the water depth is only ~137 m and so this part of the continental shelf would have been abraded through current and wave action during sea level low-stands. The fault zones on the continental shelf continue southward as the Flinders-Shoal Island fault system (Whitney et al., 2015b).

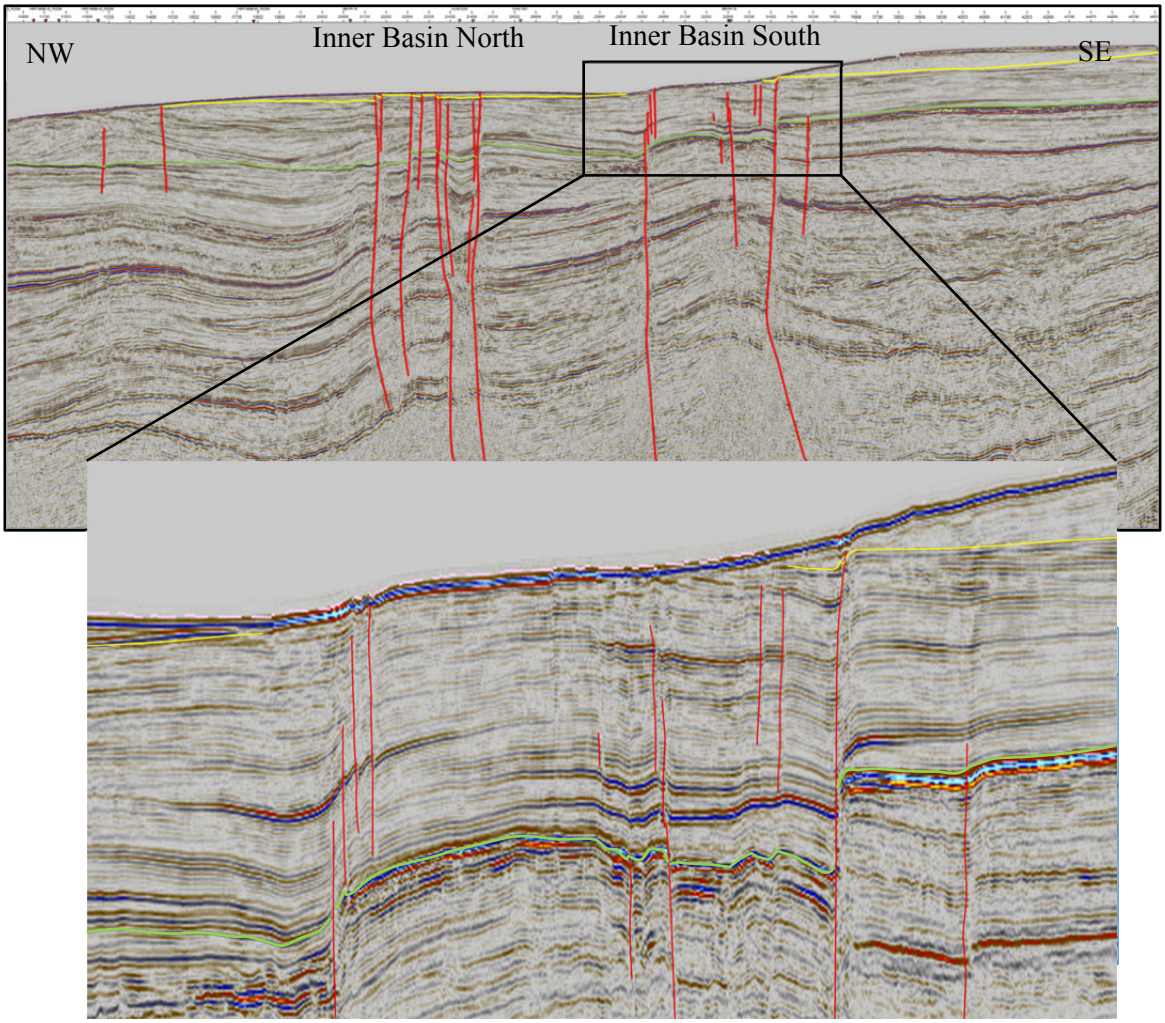

Figure 2-1. Faulting of the Pliocene and Quaternary unconformities and present-day seafloor north of Scott Reef in Browse Basin. Portion of seismic line BBHR-11.

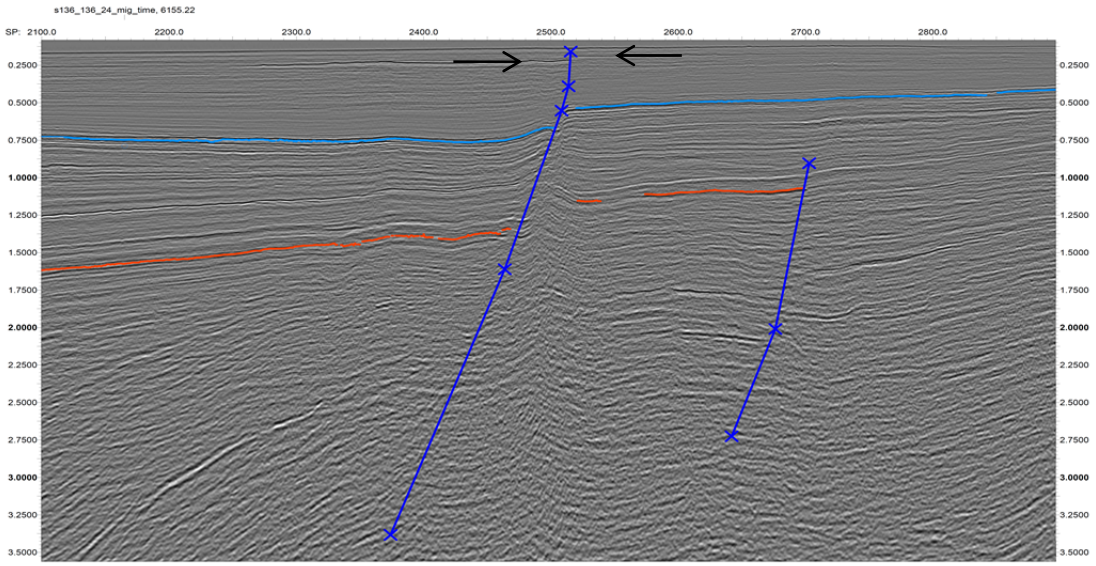

Figure 2-2. Shallow sub-bottom deformation along Inner Shelf fault zone. Blue horizon is near base Pliocene. Arrow marks likely position of Quaternary section. Red horizon is Cretaceous Turonian horizon.

3. DISCUSSION - IMPLICATIONS FOR HAZARD ASSESSMENT

The Quaternary active faults identified within the WASZ on the North West Shelf constitute significant seismic sources that should be considered in future seismic hazard assessments. A preliminary source characterization is completed below to provide an indication of the magnitude and recurrence intervals for major earthquakes on these faults. The dominant style of deformation for faults within this zone involves dextral transcurrent motion related to the collision on the northern plate boundary zone (Whitney and Hengesh, this volume) with a progressive down-to-the-west component of vertical displacement.

Fault length and fault area can be used to estimate maximum earthquake magnitude (Mmax) values for fault sources. Individual fault segments within the WASZ appear to range from approximately 70 to 250 km in length, and fault widths are estimated to be on the order of 15 km. We estimate Mmax values using five different empirical relationships between fault length and magnitude, and rupture area and magnitude, to compute Mmax distributions for each fault (Wells and Coppersmith, 1994; Hanks and Bakun, 2002; 2008; Ellsworth, 2003; Wesnousky, 2008). Where the option exists, the magnitudes were computed using relationships for strike slip faults because this is the most common style of deformation on the North West Shelf and these relations have the highest correlation coefficients (Wells and Coppersmith, 1994). The minimum, average, and maximum magnitude values are derived from the range of lengths and areas used and the range of results derived from the five different equations. This approach captures the epistemic uncertainty in the fault rupture characteristics and published empirical regressions. The resulting Mmax values are summarized in Table 3-1, below.

Based on the suite of Mmax values we estimate a distribution of mean maximum displacement values for use in recurrence calculations. Fault displacements were estimated using the Wells and Coppersmith (1994) empirical relationship between moment magnitude (Mw) and mean maximum displacement (MD) for strike slip faults. The distribution of displacement values for strike slip faults is summarized in Table 3-1.

Table 3-1. Preliminary fault characterization for selected faults in the WASZ.

Fault	Estimated Rupture Length (km)		Magnitude Distribution (Mw)			W&C MD *fx* Mw SS Displacement (m)			Slip Rate Models (mm/yr)			Recurrence (yrs) (MD fx Mw/slip rate)		
	Min	*Max*	*Min*	*Ave*	*Max*	*Min*	*Mid*	*Max*	*Min*	*Mid*	*Max*	*Min*	*Mid*	*Max*
Outer Shelf (Scott Reef)	85	170	7.05	7.38	7.66	1.70	3.73	7.21	0.4	2.0	3.0	566	1,865	18,021
Inner Shelf	83	98	7.11	7.29	7.45	1.95	2.99	4.36	0.04	0.6	2.2	886	4,601	110,019
Outer Shelf- (Rowley Shoals)	75	140	7.06	7.35	7.60	1.75	3.44	6.30	0.002	0.3	1.1	1,637	12,574	2,700,634

Note: W&C MD fx Mw SS Displacement = Wells and Coppersmith mean maximum displacement as a function of moment magnitude for strike slip faults.

To compute recurrence intervals we use observed vertical displacements and convert these to a range of estimated horizontal slip rates (Table 3-2). Rates of vertical deformation were measured from the base Pliocene unconformity, and where available the Quaternary to Holocene unconformity, shallow sub-bottom reflectors, and the seabed. In computing these rates we assume that the age of onset of deformation ranges from 1 to 3 Ma, consistent with the timing of collision along the Sumba-Savu-Rote ridge (Roosmawati and Harris, 2009; Rigg and Hall, 2011) directly north of the rifted margin. As the fault segments terminate into folds the slip rates will vary along strike.

We did not identify any suitable piercing points with which to assess horizontal slip rates across the fault zones. However, a general indication of horizontal slip rates can be estimated by assuming a range of vertical to horizontal slip ratios across the fault zone. Common horizontal to vertical slip ratios range from 1:1 to 10:1. Therefore, the estimated minimum and maximum horizontal slip rate values across the entire Western Australia Shear Zone (in Browse basin) ranges from 0.7 to 6.5 mm yr^{-1}. This range is likely a minimum as we have no data for deformation along faults on the Scott Plateau further offshore to the west.

Table 3-2. Summary of horizontal slip rate estimates in mm/yr for selected faults in the WASZ.

	Min (mm/yr)	Mid (mm/yr)	Max (mm/yr)
Outer Shelf (Scott Reef)	0.28	2.00	3.00
Inner Shelf	0.04	0.65	2.20
Outer Shelf (Rowley Shoals Fault	0.002	0.27	1.07

Based on the maximum displacement values and range of horizontal slip rate values we compute preliminary estimates of earthquake recurrence for the faults (Table 3-1). The median estimates of recurrence for Mmax events are approximately 2,000, 5,000 and 12,000 years, indicating that these faults could produce one to six large magnitude events during Holocene time. This level of activity is consistent with the recurrence interval of approximately several hundred to ~1,000 years for events of M_w 7 to 7.5 along the entire NWS (Fig 3-1).

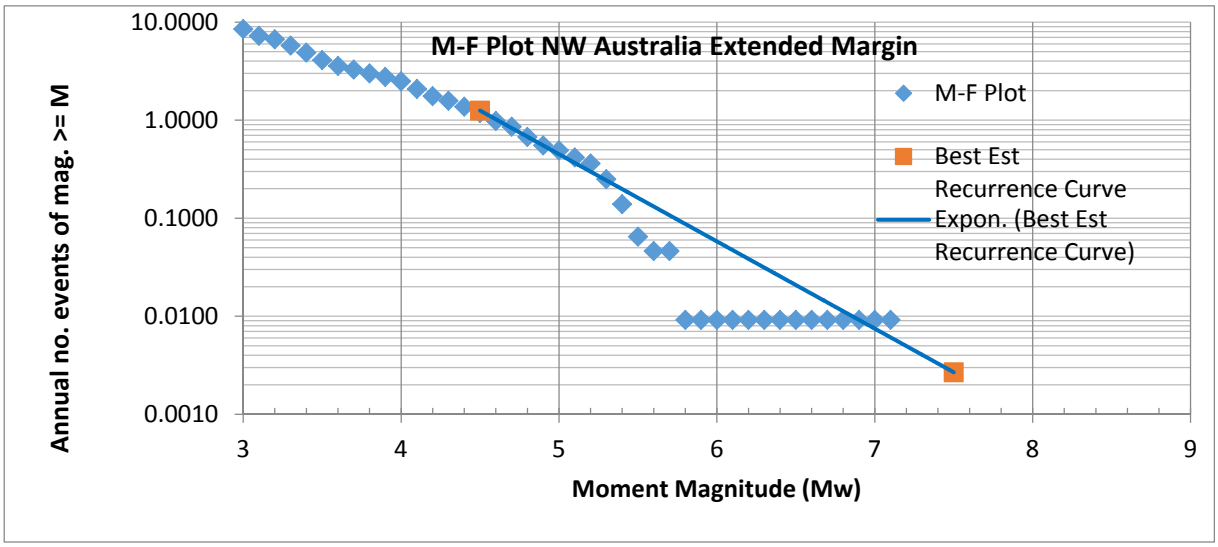

Figure 3-1. Magnitude-frequency plot for the northwestern Australian extended margin.

4. CONCLUSIONS

The Mesozoic extended margin of western Australia is being reactivated as a transcurrent fault system due to the transition from subduction to continent-arc collision on the northern plate boundary. The fault system extends 1,400 km along the North West Shelf from Ashmore Reef to the Cape Range. It then extends an additional 600 km through a system of folds and faults in the southern Carnarvon basin to the western edge of the Yilgarn craton (Whitney & Hengesh, this volume). This fault system is referred to as the Western Australia Shear Zone (WASZ) (Whitney, 2015).

Preliminary seismic source characterizations have been completed for the Outer Shelf fault zone between Scott Reef and Rowley Shoals, and the Inner Shelf fault zone offshore of Dampier to provide examples of the magnitude, slip rate, and recurrence characteristics of faults in the WASZ. Our analyses indicate that individual fault segments may produce Mmax earthquakes that range in

magnitude from M_w 7.1 to 7.6 with average recurrence intervals of roughly 2,000 to 12,000 years. These values are generally consistent with seismologically based magnitude frequency relationships that suggest recurrence intervals of a few hundred to about 1,000 years for magnitude 7.0 to 7.5 events on the western extended margin. These structures pose significant seismic hazards and should be considered in future seismic hazard analyses for critical facilities on the NWS.

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