Knight Piésold
CONSULTING

MEMORANDUM

To:	**Venturex Resources Limited**	**Date:**	21st November 2017
Attn:	Emma Bamforth	**Our Ref:**	PE17-01074
		KP File Ref.:	PE801-00300/05-A jl M17007
cc:		**From:**	Zhenhe Song/Jim Luo

RE: SULPHUR SPRINGS – PRELIMINARY SEISMIC HAZARD ASSESSMENT

1. INTRODUCTION

Venturex Resources Ltd (Venturex) is undertaking a definitive feasibility study for the Sulphur Springs Copper – Zinc Project. Knight Piésold Pty Ltd (KP) has been to undertake the tailings management aspects of the project study.

A seismic hazard assessment has been carried out for the project site. Existing information and historical data, including earthquake catalogues and technical publications have been collected and reviewed. Seismic ground motion parameters for the project area have also been determined. The Sulphur Springs project site is located 144 km south-east of Port Hedland in northern Western Australia at approximate coordinates of Latitude -21.14° and Longitude 119.22°.

2. REGIONAL SEISMICITY

The seismicity of much of Australia is typical of an intra-plate region, characterised by low levels of seismic activity and earthquakes apparently randomly distributed in location and time. The correlation between recorded earthquakes and geological features is typically not well known or understood.

The site is located on the Pilbara Craton which is one of the oldest blocks in Australia, and preserves tectonic evolution features that formed between circa 3.65 and 2.0 Ga (Ref. 1, Betts et al., 2002). The crustal growth in the eastern Pilbara occurred between 3.65 and 3.15 Ga and comprises dome structures in a granite-greenstone lithology. This lithology may indicate a different composition of continental crust formation than at present, although the western part of the Pilbara is comparable to present day tectonic processes. The convective overturn model is used to explain the 100 km-scale granitoid domes (Ref. 2, Collins et al. 1998 and Ref. 3 Collins and Van Kranendonk 1999). Zegers et al. (Ref. 4, 1996) observed large shear zones which evolved in an extensional environment (Betts et al., 2002). The location of the Pilbara Craton is illustrated in figures 2.1 and 2.2.

Historical earthquake data for the extended area surrounding the Sulphur Springs project site was obtained from the Geoscience Australia (GA, Ref. 5) and International Seismological Centre (ISC, Ref. 6) earthquake databases and includes all recorded earthquakes (M1.0 and above) within the region between 1929 and 2017. This data indicates that 478 earthquakes have occurred within 500 km of the project site with earthquake magnitudes in the range of M1.8 to M6.6. Seven of the earthquakes in the GA database were recorded to have occurred within 50 km of the site, with the closest occurring in 1971, located approximately 16 km north-east of the site, and with a magnitude of M2.7. The M6.6 earthquake occurred in 1929 approximately 480 km from the site, and located offshore Western Australia.

The locations of historic earthquakes and seismic source zones (Geoscience Australia, Refs. 7 and 8) are shown in Figure 2.3. Figure 2.4 illustrates the magnitude distribution versus depth and the earthquake depth histogram. As Australia is an intra-plate region, the earthquakes generally occur at shallow depths within the Earth's crust (i.e. with focal depths less than 40 km).

3. PROBABILISTIC ANALYSIS

The computer program OpenQuake (Global Earthquake Model (GEM), Ref. 9, 2017) was used to develop a probabilistic seismic hazard model for the site. The OpenQuake engine is seismic hazard and risk calculation software developed by GEM.

GEM implemented the 2012 Australian seismic hazard assessment by GA (Ref. 7) in the OpenQuake engine. The seismic source model consists of three different layers of seismic sources: continental-scale background zones, regional-scale area sources, and small-scale (hot spots) zones describing localised seismic sequences. The source zonation correlates well with the historic earthquake catalogue shown in Figure 2.3. Based on the source zones prepared by GA, a total of 18 seismic sources within 600 km of the project site were considered in the seismic hazard assessment. These include fourteen cratonic models and four non-cratonic models.

The Ground Motion Predictive Equations (GMPEs) used to determine the seismic hazard for the Sulphur Springs project comprise the four GMPEs recommended by GA in the 2012 seismic hazard assessment. The ground motion model distinguishes between two main tectonic regions: Cratonic and non-Cratonic. For each tectonic region the model considers multiple ground motion prediction equations organised in a logic tree structure. Table 3.1 shows the GMPEs used in the current seismic hazard assessment.

Table 3.1: GMPEs used in the 2012 Australian Hazard Assessment for Cratonic regions

Cratonic GMPEs	Weight
Allen 2012, Ref. 10	0.3
Atkinson and Boore 2006, Ref. 11	0.3
Chiou and Youngs 2008, Ref. 12	0.1
Somerville et. al. 2009 (for Yilgarn Craton), Ref. 13	0.3

The probabilistic analysis was used to estimate the peak ground accelerations for seismic events with different annual frequencies of occurrence. The peak ground acceleration (PGA) was calculated for each attenuation model and the mean values of peak ground acceleration have been determined for return periods ranging from 100 to 10,000 years.

Seismic hazard was computed in accordance with the methodology described in GA, 2012 (Ref. 7). Separate hazard calculations were carried out for the background and regional model, and for the hot spots model. If the hot spot model predicted a higher hazard level than the background and regional models, the mean of the two was taken.

Table 3.2 presents the estimated peak ground accelerations and probabilities of exceedance corresponding to earthquake return periods of between 100 and 10,000 years and design lives of 10, 20, 30 and 50 years respectively. The peak ground accelerations are the weighted average values calculated from the attenuation functions used in OpenQuake. These results are also shown graphically in Figure 3.1.

Table 3.2: Summary of probabilistic analysis

Return Period (Years)	Annual Frequency of Exceedance	Probability of Exceedance for Design Life				Peak Ground Acceleration (g)
		10 years	20 years	30 years	50 years	
100	0.01	9.5%	18.1%	25.9%	39.3%	0.015
250	0.004	3.9%	7.7%	11.3%	18.1%	0.033
500	0.002	2.0%	3.9%	5.8%	9.5%	0.058
1,000	0.001	1.0%	2.0%	3.0%	4.9%	0.098
2,500	0.0004	0.4%	0.8%	1.2%	2.0%	0.191
10,000	0.0001	0.1%	0.2%	0.3%	0.5%	0.481

Regional PGA (peak ground acceleration) corresponding to return intervals of 500 and 2500 years are presented in the GA seismic hazard maps (Ref. 8), copies of which are included in Figure 3.2. The PGAs estimated by GA are:

- Earthquake with a return period of 500 years - approximately 0.06g
- Earthquake with a return period of 2,500 years - approximately 0.19g

These PGAs are generally consistent with the current assessment results summarised in Table 3.2.

For this study, the average shear wave velocity in the top 30 m has been assumed to be 760 m/s, which straddles the boundary between Site Class B and C (‘rock’ and ‘very dense soil and soft rock’), as defined by the ASCE/SEI (Ref. 14). Peak ground accelerations on top of the foundation material, the tailings and embankment dam may be higher due to amplification of ground motion. The ability of the foundation materials, embankment fills and tailings slurry to transmit high seismic ground motions is dependent on their dynamic stiffness and damping characteristics. Dynamic site response analyses can determine whether amplification or attenuation of the seismic waves will occur through the foundation materials, tailings deposit and embankment dam. Separate analysis is required to determine the acceleration within the tailings facility due to a seismic event.

4. SEISMIC DESIGN PARAMETERS

4.1 TAILING STORAGE FACILITY

4.1.1 Seismic Design Categories

According to the ANCOLD (Ref. 15 and 16) guidelines for tailings dams, three levels of design earthquake are typically considered: Operating Basis Earthquake (OBE) for normal operations; Maximum Design Earthquake (MDE) for extreme (dam safety) conditions during operations; and Maximum Credible Earthquake (MCE) for post closure stability.

Appropriate return intervals for the design earthquakes need to be determined based on the consequence category for the TSF, which considers the consequences of failure. This assessment typically includes consideration of the potential loss of life and environmental and economic impacts due to failure of the tailings dam (Ref. 15 and 16). For the purposes of this assessment it has been assumed that the TSF will be classified as either a significant or high consequence category facility. This will be determined as part of the design process.

The recommended design earthquake return interval by consequence category are summarised in Table 4.1.

Table 4.1: Recommended Design Earthquake Return Periods (AEP)

Dam Failure Consequence Category	Operations Phase		Post Closure
	OBE	MDE	
Low	1:50	1:100	MCE
Significant	1:100	1:1,000	MCE
High/Extreme	1:1,000	1:10,000	MCE

From ANCOLD (2012), Guidelines on Tailings Dams

4.1.2 Operating Basis Earthquake

The OBE is typically determined using probabilistic seismic hazard analysis to select an acceptable level of risk, based on the probability of exceedance over the design life of the facility. Consideration is also given to the consequence category of the facility, which considers the consequences of dam failure. This assessment includes consideration of the potential loss of life, and environmental and economic impacts due to failure of the tailings dam (Refs. 15 and 16).

The ANCOLD guidelines (Ref. 16) recommend that the 1 in 100 year or 1 in 1,000 year earthquake be adopted for the OBE, based on a consequence category of significant or high respectively. The PGAs for an OBE earthquake are calculated in the probabilistic analysis as:

- 1 in 100 year return period earthquake PGA of 0.015g (significant consequence category).
- 1 in 1,000 year return period earthquake PGA of 0.098g (high consequence category).

The uniform hazard spectra 100 and 1,000 year return periods are presented in Figure 4.1. The following earthquake scenarios were selected based on a review of historical seismicity and the findings of the seismic hazard analyses (including de-aggregation of the seismic hazard).

- A design earthquake of magnitude M5.5 located at a distance of approximately 55 km and a focal depth of 10 km has been selected for the 1 in 100 year OBE, based on median probability.
- A design earthquake of magnitude M6.3 located at a distance of approximately 32 km and a focal depth of 10 km has been selected for the 1 in 1,000 year OBE, based on median probability.

Dams should remain serviceable under the OBE. The OBE is generally expected to cause limited damage/deformation that could be repaired without significantly disrupting operations (Ref. 16).

4.1.3 Maximum Design Earthquake

An appropriate MDE for a TSF is typically determined based on the Consequence Category of the facility. In accordance with the ANCOLD guideline (Ref. 16) it is recommended that the 1 in 1,000 or 1 in 10,000 year peak ground acceleration be adopted for the MDE, based on a significant or high consequence category respectively. The PGAs for an MDE earthquake are calculated in the probabilistic analysis as:

- 1 in 1,000 year return period earthquake PGA of 0.098g (based on a significant consequence category).

- 1 in 10,000 year return period earthquake PGA of 0.481g (based on a high consequence category).

The uniform hazard spectra for return periods of 1,000 and 10,000 years are presented in Figure 4.1. The following earthquake scenarios were selected based on a review of historical seismicity and the findings of the seismic hazard analyses (including de-aggregation of the seismic hazard).

- A design earthquake of magnitude M6.3 located at a distance of approximately 32 km and a focal depth of 10 km has been selected for the 1 in 1,000 year MDE, based on median probability.
- A design earthquake of magnitude M7.5 located at a distance of approximately 19 km and a focal depth of 10 km has been selected for the 1 in 10,000 year MDE, based on median probability.

Damage under the MDE could be more extensive and may disrupt operations, but the structural integrity of the dam should be maintained and uncontrolled release of tailings/water should not occur (Ref. 16).

4.1.4 Maximum Credible Earthquake

The MCE is considered to be the maximum credible acceleration that can occur, on the basis of available seismic and tectonic information. The MCE is calculated deterministically and, therefore, is not associated with a return period. The MCE is the maximum ground motion attributable to all large magnitude earthquakes that could ever occur at the site (Ref. 16).

The GA 2012 seismic hazard assessment shows that the site is located within a seismic zone able to generate large earthquakes up to M7.5. In addition, the hot spot seismic source zone is located approximately 15 km east of the site and is thought to be capable of producing earthquakes up to M6.3. The results of the probabilistic analysis indicate these two source zones to be the main contributor to the site’s seismic hazard, with the other seismic sources located too far from the site to contribute significantly to the seismic hazard.

As such, the MCE scenario assumes that a M7.5 shallow crustal earthquake occurs within 20 km of the site, causing a PGA of 0.45g. Comparison with the probabilistic analysis results indicates this acceleration to be similar to the PGA calculated for the 1 in 10,000 year return interval, which is indicative of the long return period associated with such a large earthquake occurring in the region.

The long term properties of the tailings should be taken into account when considering stability of the TSF under the MCE. This could include lowered phreatic surface and increased strength from consolidation and possible chemical bonding (Ref. 15).

4.2 STRUCTURAL DESIGN

Building structures for the project should be designed to an appropriate seismic design code such as the International Building Code (IBC, Ref. 17). Seismic design in accordance with the IBC requires determination of seismic coefficients, SS and S1, defined as follows:

- Seismic coefficient, SS: maximum considered earthquake ground motion of 0.2 seconds spectral response acceleration (5% of critical damping).
- Seismic coefficient, S1: maximum considered earthquake ground motion of 1.0 second spectral response acceleration (5% of critical damping).

In accordance with the IBC, the maximum considered earthquake ground motion has been defined as the ground motion with a 2% probability of exceedance in 50 years (return period of 2,500 years). Specific seismic design parameters for use with the IBC are provided below:

- Peak Ground Acceleration = 0.191g.
- Seismic coefficient, SS = 0.285g.
- Seismic coefficient, S1 = 0.073g.

These values correspond to assumed ground conditions of Site Class B / C, defined by ASCE/SEI 7-10 (Ref. 14) as very dense soil and soft rock to rock with an average shear wave velocity of 760 m/s in the top 30 m. The site classification system according to ASCE/SEI 7-10 is provided in Table 4.2. PGAs of the foundation material will be determined in relation to the site classification and appropriate amplification factors according to ASCE/SEI 7-10, following completion of the site geotechnical investigation.

Table 4.2: Site Classification (Adapted from ASCE/SEI 7-10, Table 20.3-1)

Site Class	Soil profile name	Average properties in top 30 m		
		Soil shear wave velocity, v_s, (m/s)	Standard Penetration Resistance, N	Soil undrained shear strength, s_u (kPa)
A	Hard rock	$v_s > 1{,}500$	N/A	N/A
B	Rock	$760 < v_s \le 1{,}500$	N/A	N/A
C	Very dense soil and soft rock	$360 < v_s \le 760$	$N \ge 50$	$s_u \ge 96$
D	Stiff soil	$180 < v_s \le 360$	$15 \le N \le 50$	$48 \le s_u \le 96$
E	Soft clay soil	$v_s < 180$	$N \le 15$	$s_u \le 48$
		Any profile with more than 3 m of soil with the following characteristics: 1. Plasticity index PI > 20, 2. Moisture content $w \ge 40\%$ and 3. Undrained shear strength $s_u < 24$		
F	Soils requiring site response analysis in accordance with Section 21.1	Any profile containing soils having one or more of the following characteristics: 1. Soils vulnerable to potential failure or collapse under seismic loading, such as liquefiable soils, quick and highly sensitive clays, and collapsible weakly cemented soils. 2. Peats and/or highly organic clays (H > 3 m) of peat and/or highly organic clay where H = thickness of soil). 3. Very high plasticity clays (H > 7.6 m with PI > 75). 4. Very thick soft/medium stiff clays (H > 37 m) with $s_u < 48$		

For the foundation design of mine site structures an earthquake magnitude of M6.5 at a distance of approximately 23 km and focal depth of approximately 10 km is recommended for seismic design analyses (including soil liquefaction assessment, if required), based on the findings of the seismic hazard analyses (including de-aggregation of the probabilistic seismic hazard). The structural response spectrum for the 1 in 2,500 year earthquake is presented in Figure 4.2.

5. SUMMARY

A site specific seismic hazard assessment has been carried out for the Sulphur Springs project. The assessment includes probabilistic and deterministic seismic hazard analyses.

Available historical data, earthquake catalogues, and technical publications on the tectonics and seismicity of the region have been reviewed.

The computer program OpenQuake was used to develop a probabilistic seismic hazard model for the site. Appropriate attenuation models defining the relationship between earthquake magnitude, source to site distance, and peak ground acceleration have been used in the probabilistic and deterministic hazard analyses.

Seismic design parameters have been recommended for the design of critical facilities, including the tailings storage facility (TSF) and process plant site structures at the site. Seismic ground motion parameters (including peak ground acceleration and earthquake magnitude) have been estimated based on probabilistic seismic hazard analyses.

It is recommended that the 1 in 100 year earthquake or 1,000 year earthquake is adopted for the OBE, based on a significant or high consequence category. The estimated mean values of PGA are:

- 1 in 100 year return period earthquake PGA of 0.015g based on a significant consequence category. A design earthquake of magnitude M5.5 located at a distance of approximately 55 km and a focal depth of 10 km has been selected for the 1 in 100 year OBE based on median probability.
- 1 in 1,000 year return period earthquake PGA of 0.098g based on a high consequence category. A design earthquake of magnitude M6.3 located at a distance of approximately 32 km and a focal depth of 10 km has been selected for the 1 in 1,000 year OBE based on median probability.

The tailings dam and appurtenances are expected to remain functional and any damage from the occurrence of earthquake shaking not exceeding the OBE should be easily repairable.

It is recommended that the 1 in 1,000 year earthquake or 1 in 10,000 year peak ground acceleration is adopted for the MDE, based on a significant or high consequence category. The estimated mean values of PGA are:

- 1 in 1,000 year return period earthquake PGA of 0.098g based on a significant consequence category. A design earthquake of magnitude M6.3 located at a distance of approximately 32 km and a focal depth of 10 km has been selected for the 1 in 1,000 year MDE based on median probability.
- 1 in 10,000 year return period earthquake PGA of 0.481g based on a high consequence category. A design earthquake of magnitude M7.5 located at a distance of approximately 19 km and a focal depth of 10 km has been selected for the 1 in 10,000 year MDE based on median probability.

Limited deformation of the tailings dam is acceptable under seismic loading from the MDE events, provided that the overall stability and integrity of the facility is maintained and that there is no release of stored tailings or water.

The MCE scenario assumes that a M7.5 shallow crustal earthquake occurs within 20 km of the site producing a PGA of 0.45g. Comparison with the probabilistic analysis results indicates that this acceleration is similar to the PGA calculated for the 1 in 10,000 year return interval. The long term properties of the tailings should be taken into account when considering stability under the MCE. This could include lowered phreatic surface and increased strength from consolidation, and possible chemical bonding.

Parameters have also been provided for the seismic design of structures in accordance with the International Building Code (IBC). Seismic design in accordance with the IBC requires seismic parameters that correspond to spectral response acceleration values for ground motion with a 2% probability of exceedance in 50 years (return period of about 2,500 years). These values have been obtained from the probabilistic seismic hazard analysis completed for the site. A design earthquake magnitude of M6.5 at a distance of approximately 23 km and focal depth of approximately 10 km is recommended for geotechnical foundation design of the mine site structures.

The accelerations provided in this report assume that the site conditions conform to the boundary between Site Class B and C, defined by ASCE/SEI 7-10 as stiff soil to very dense soil and soft rock with an average shear wave velocity of 760 m/s in the top 30 m. The local foundation conditions will need to be classified according to IBC requirements to account for potential seismic site response (amplification of ground motions). Appropriate amplification factors shall be applied according to the site classification after completion of the geotechnical investigation.

We trust that the information provided in this memorandum is sufficient for your requirements. Kindly contact us should you have any queries.

Yours faithfully
KNIGHT PIÉSOLD PTY LTD

ZHENHE SONG
Senior Geotechnical Engineer

JIM LUO
Principal Geotechnical Engineer

6 REFERENCES

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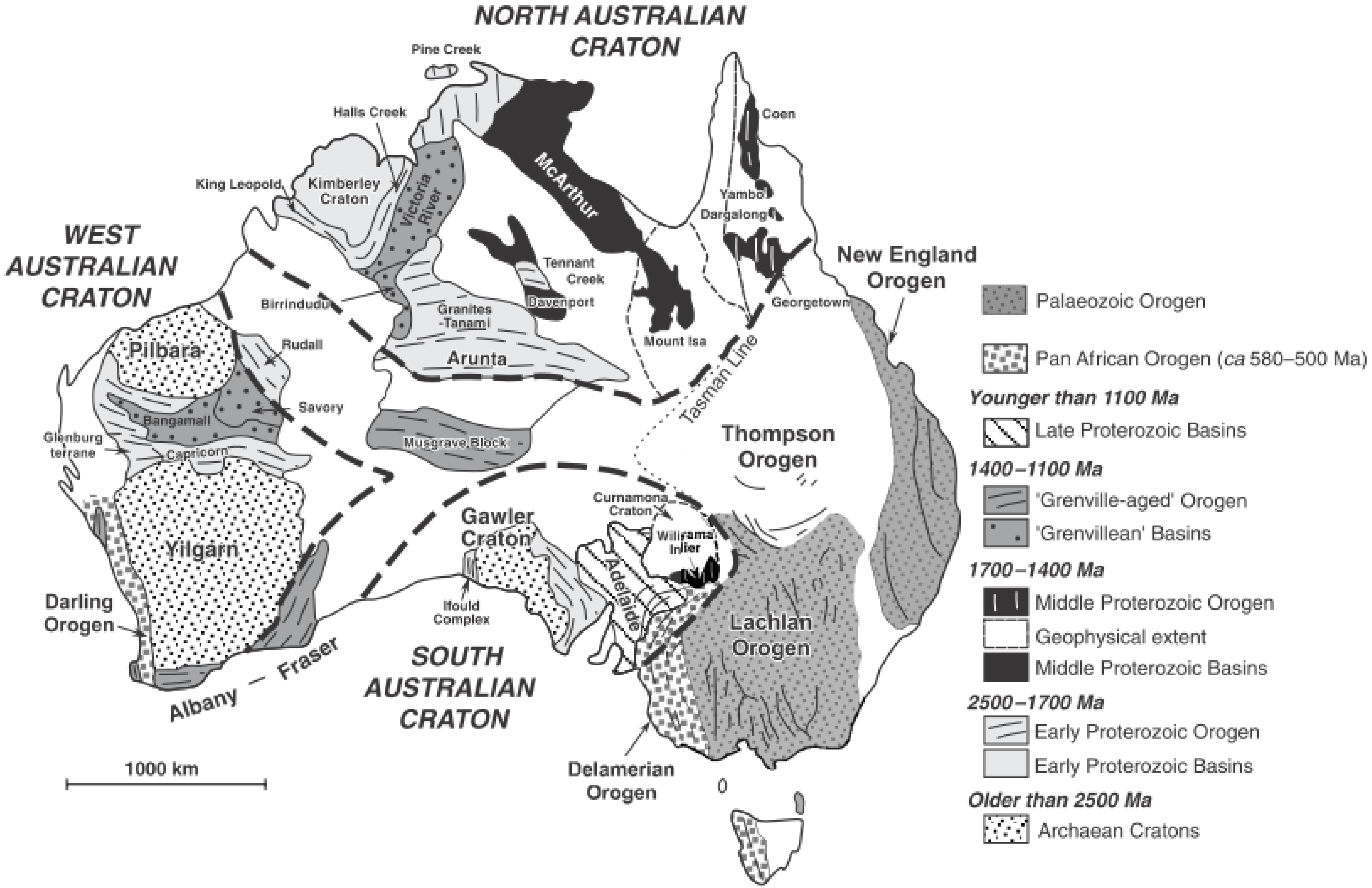
FIGURES



Ref. Betts et al., 2002

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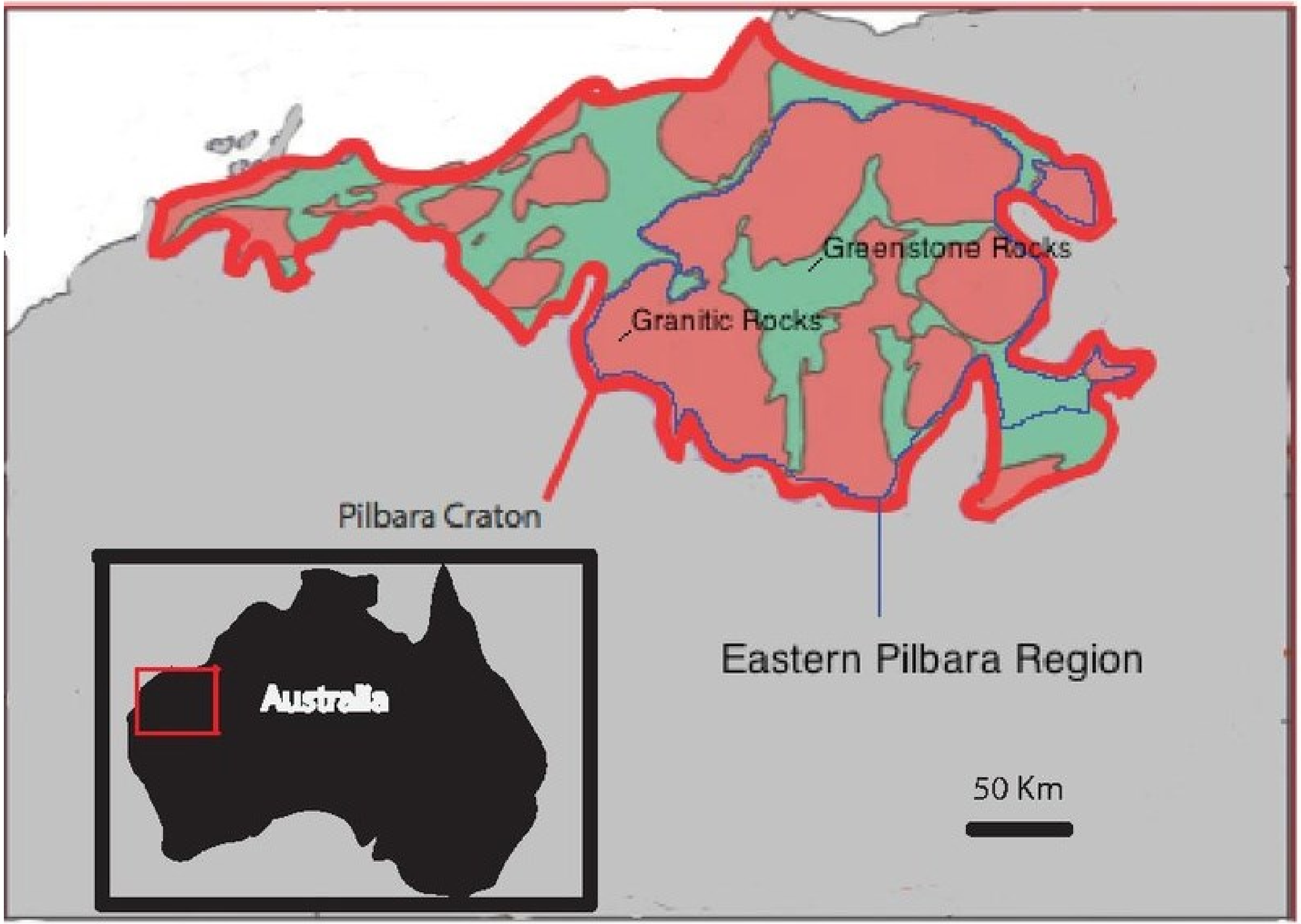
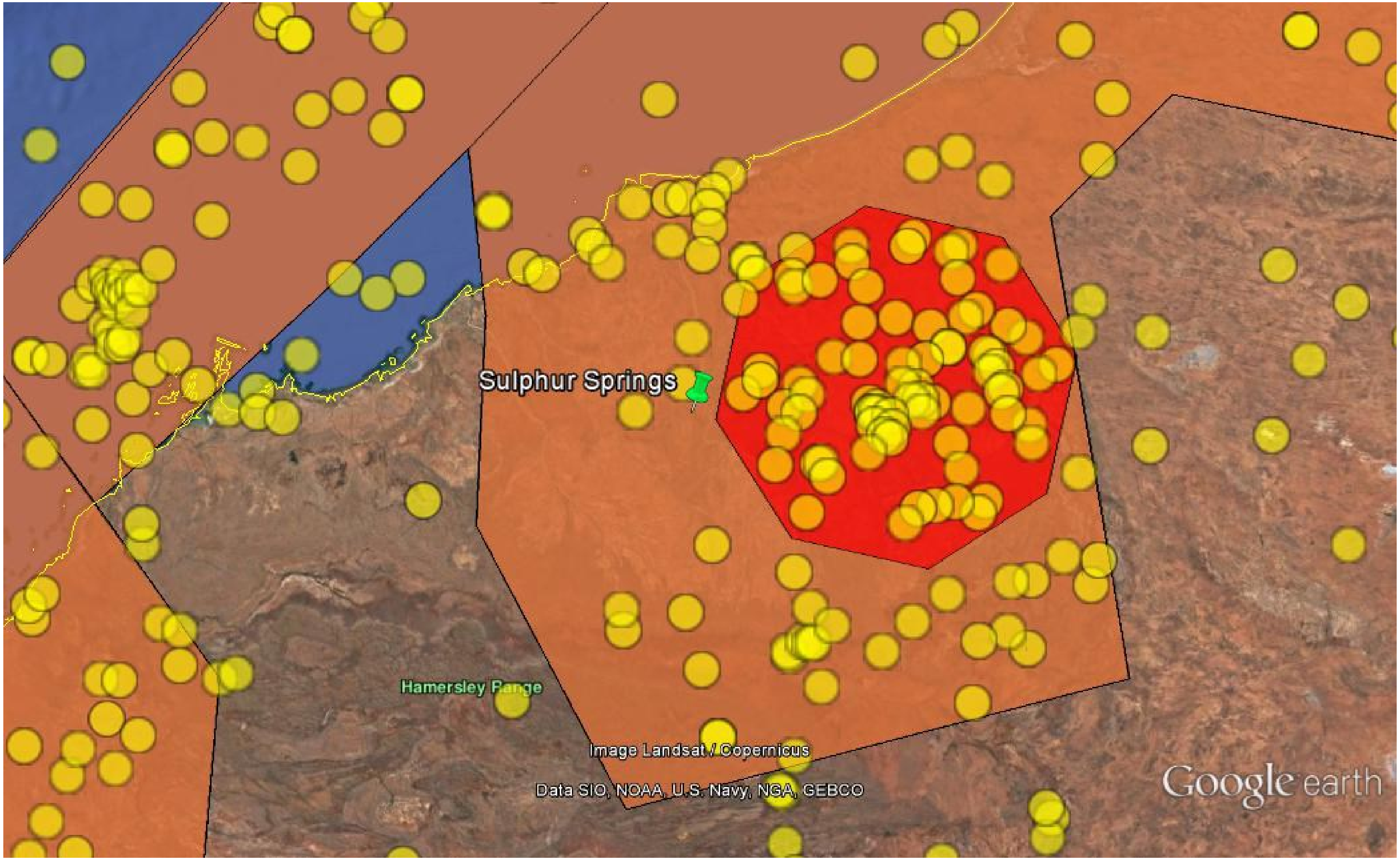
SULPHUR SPRINGS PROJECT
SEISMIC HAZARD ASSESSMENT
AUSTRALIAN PLATE TECTONIC MAP

Ref: PE801-00300 M17007
Figure 2.1



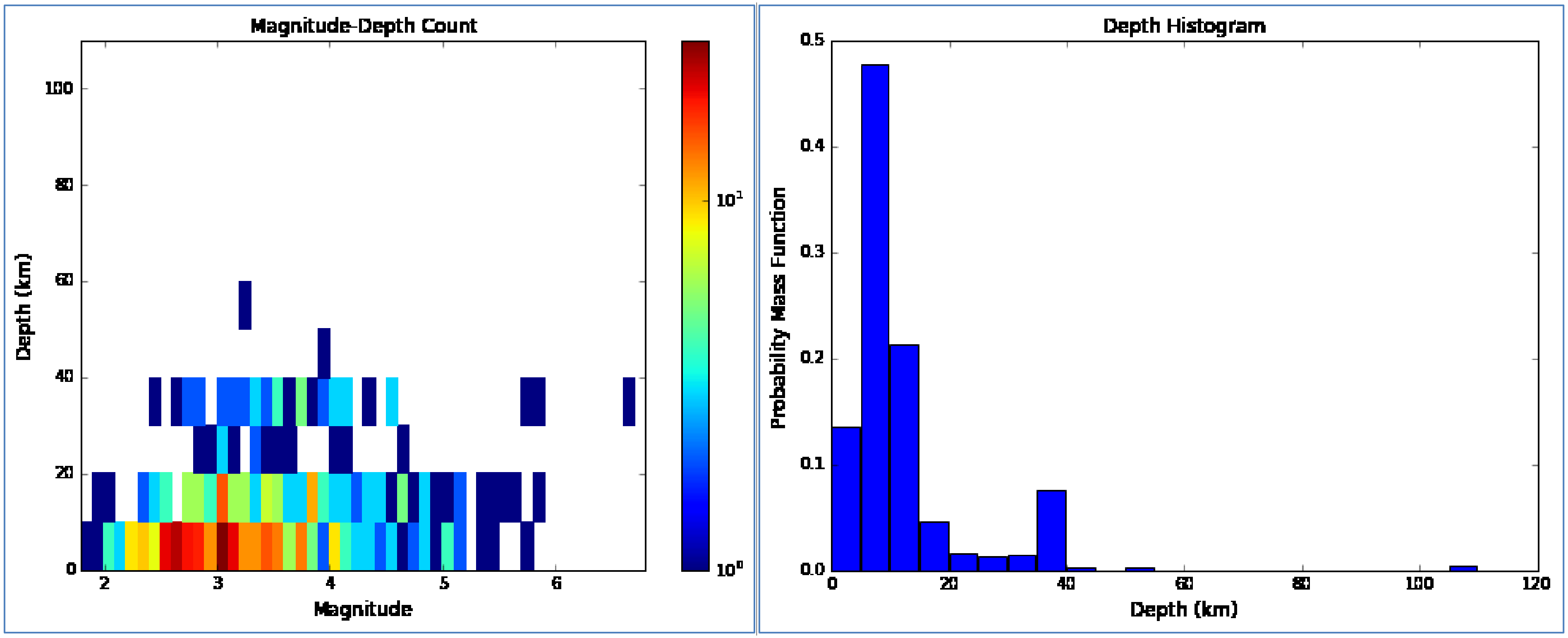
Ref: https://en.wikipedia.org/wiki/Eastern_Pilbara_Craton



Ref: Google Earth / Earthquake Date and Seismic Zones from Geoscience Australia (brown: regional source; red: hotspot source)

SULPHUR SPRINGS PROJECT
SEISMIC HAZARD ASSESSMENT
HISTORICAL EARTHQUAKE SOURCES

Ref: PE801-00300 M17007
Figure 2.3



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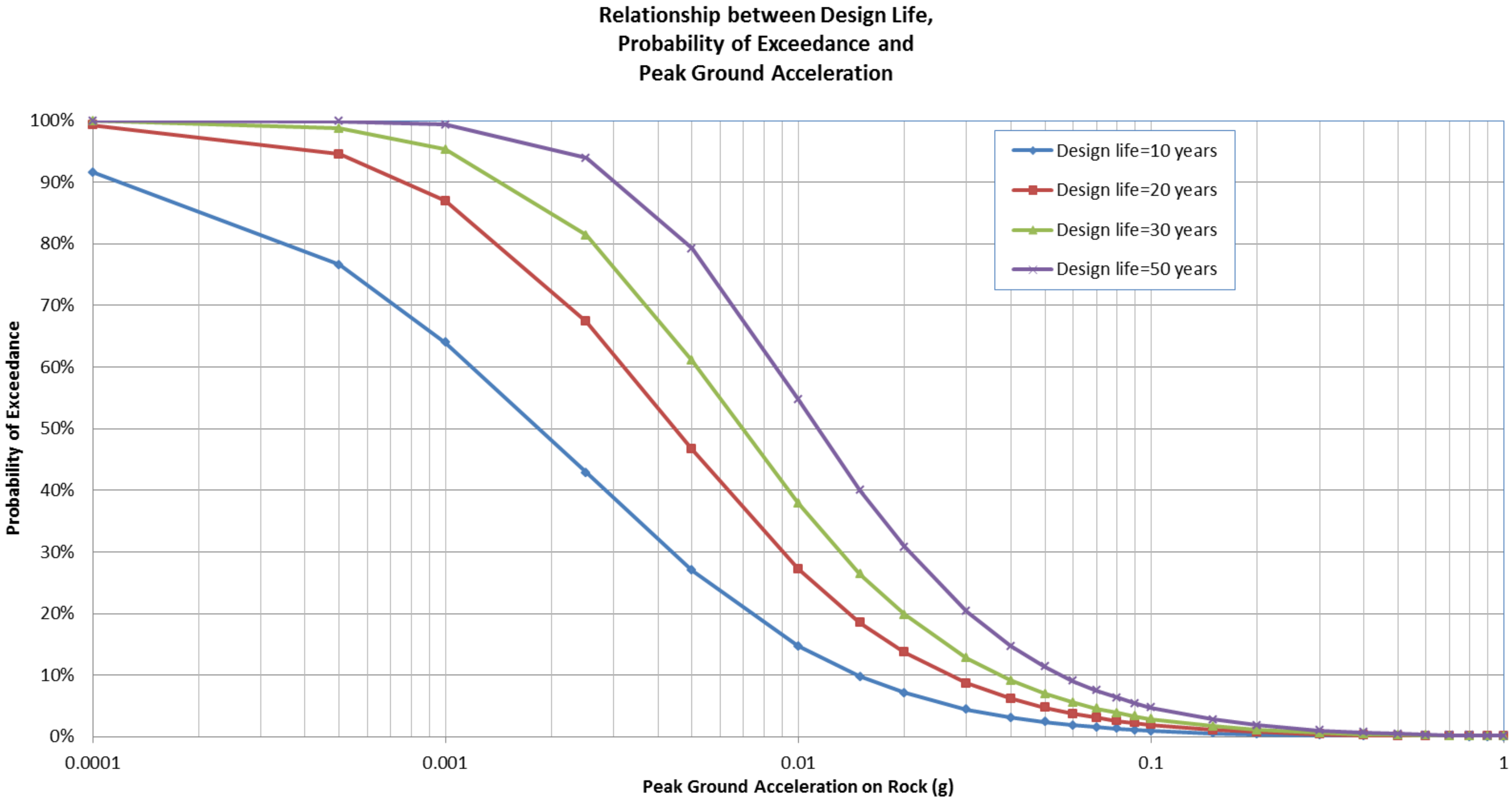
SULPHUR SPRINGS PROJECT
SEISMIC HAZARD ASSESSMENT
HISTORICAL EARTHQUAKE MAGNITUDE AND DEPTH DISTRIBUTION

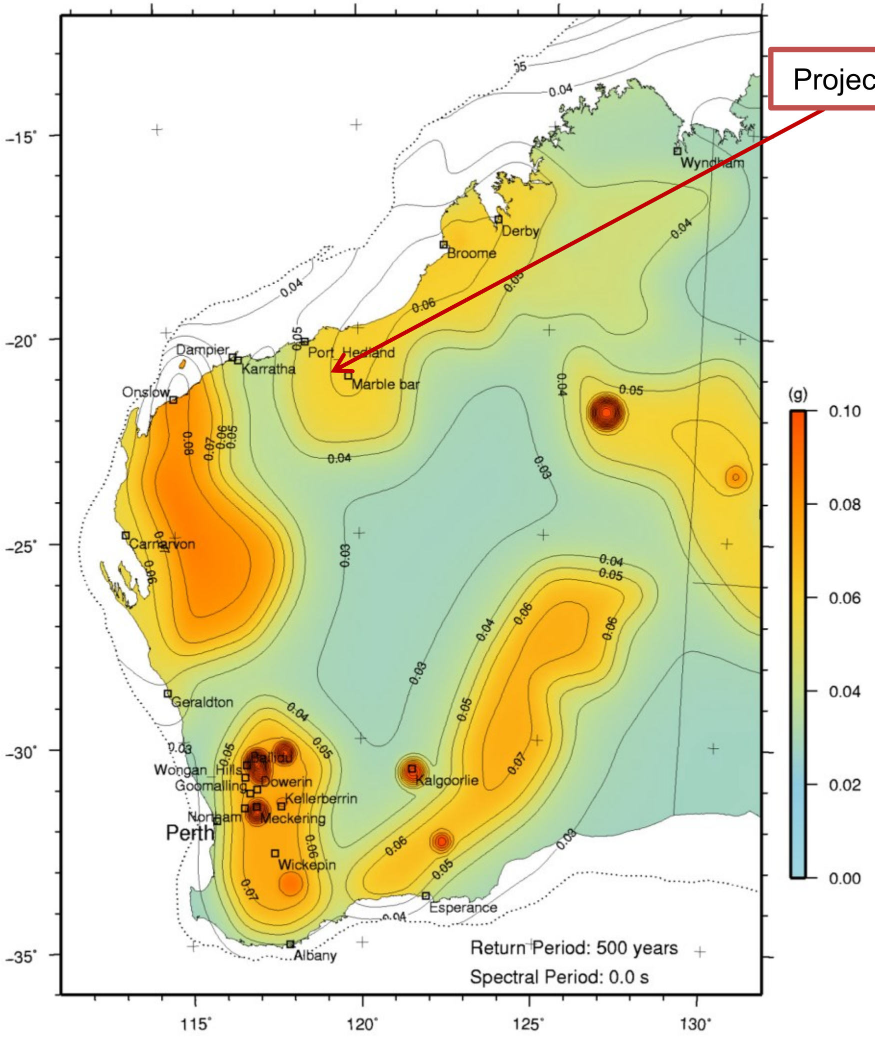
Ref: PE801-00300 M17007
Figure 2.4



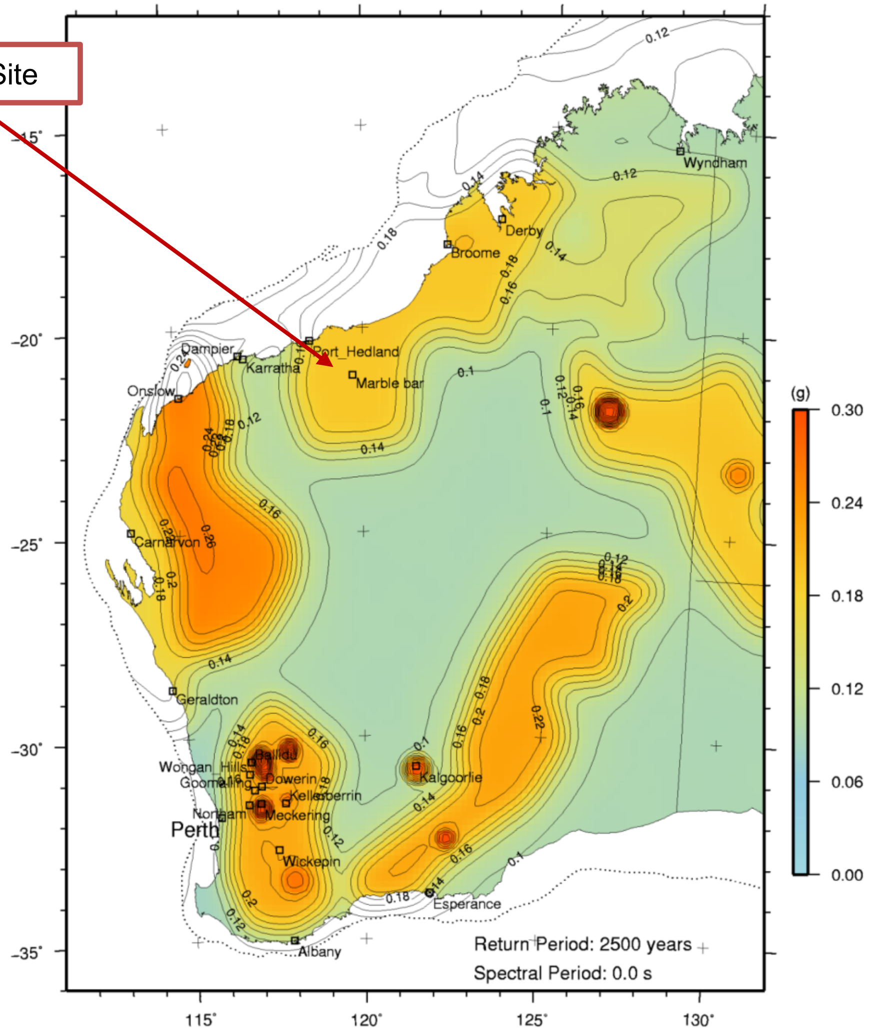
SULPHUR SPRINGS PROJECT
SEISMIC HAZARD ASSESSMENT
RELATIONSHIP BETWEEN PEAK ACCELERATION, PROBABILITY OF EXCEEDANCE AND DESIGN LIFE

Ref: PE801-00300 M17007
Figure 3.1

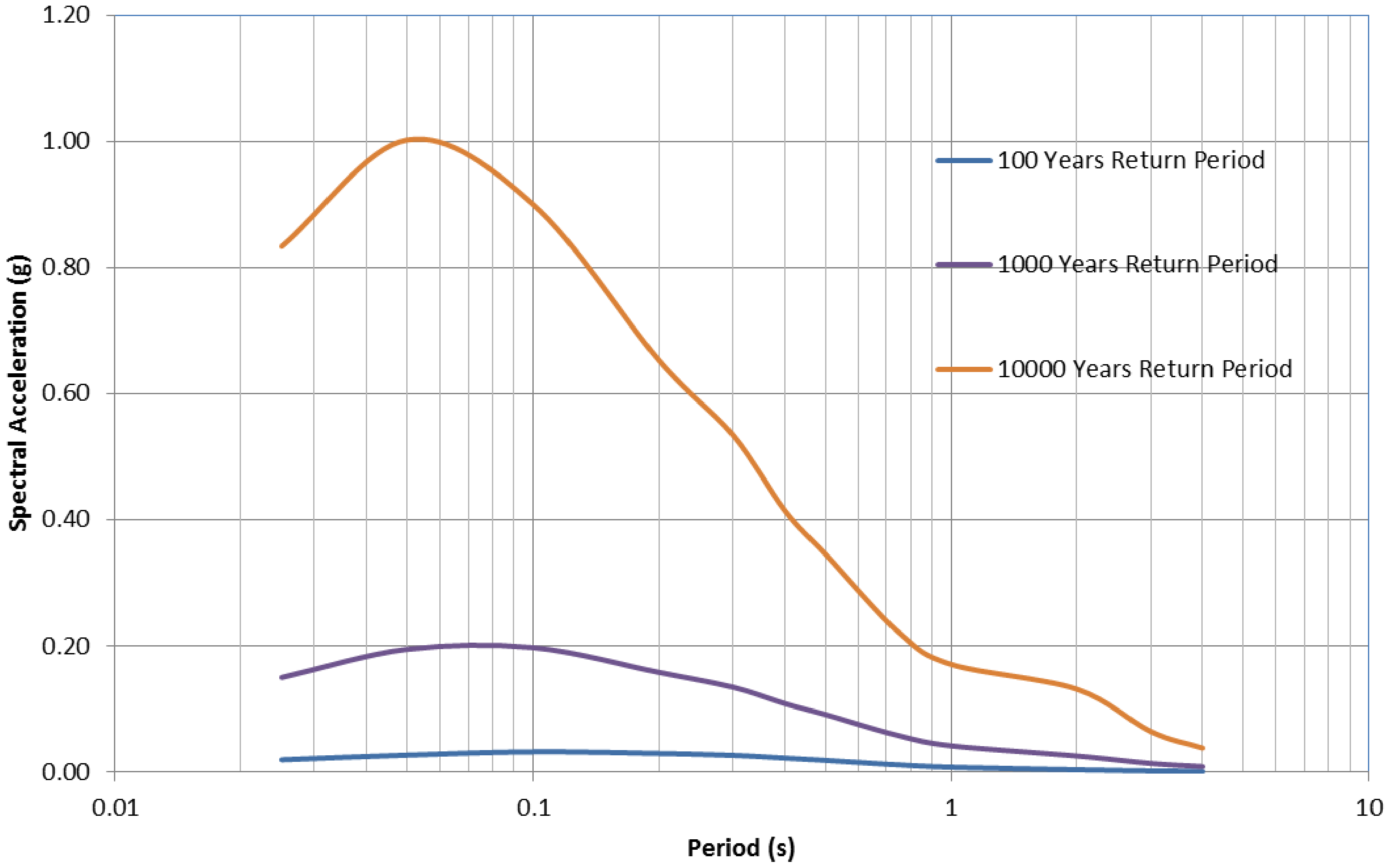
Project Site



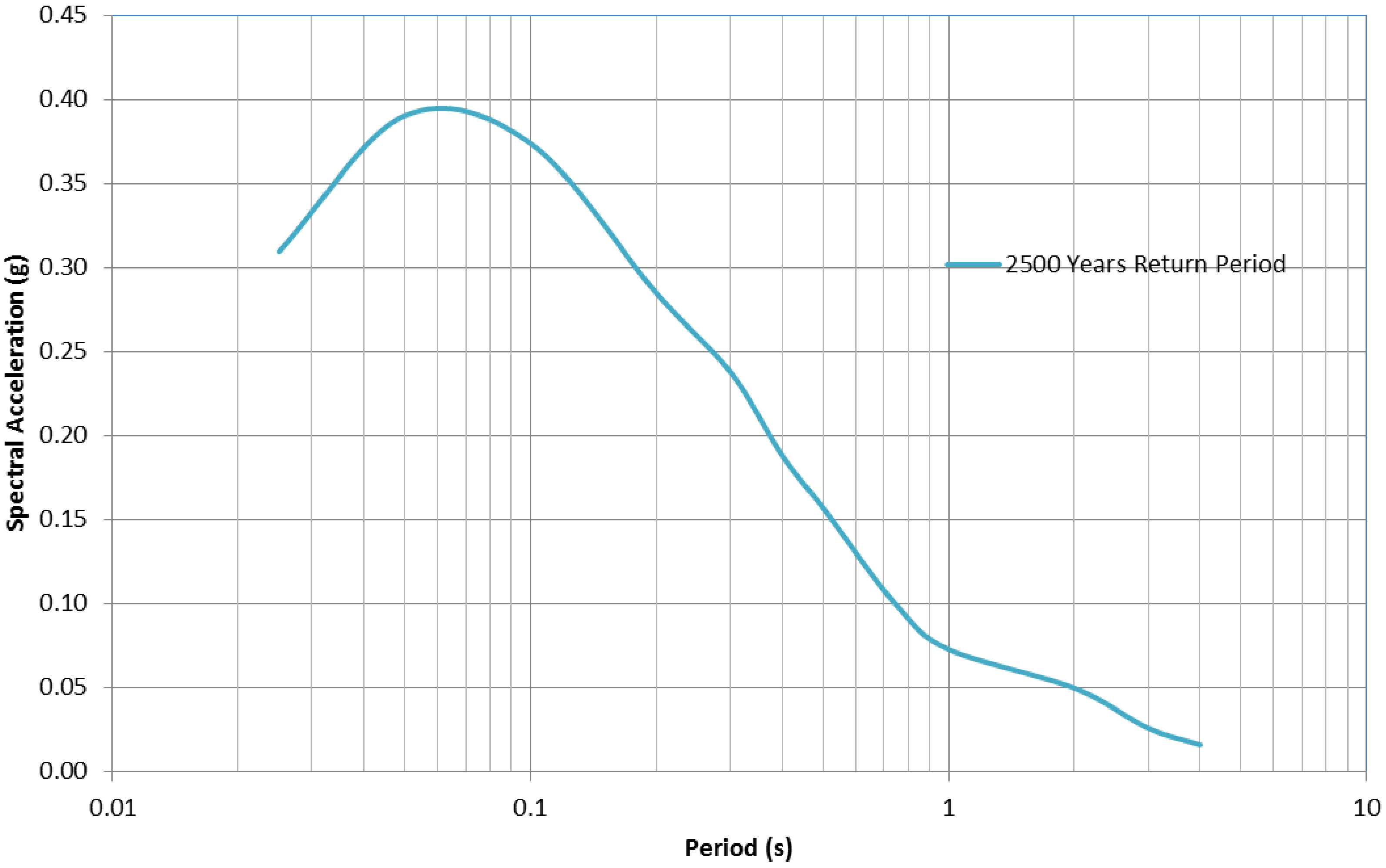
1/500 year return period PGA



1/2500 year return period PGA



SULPHUR SPRINGS PROJECT
SEISMIC HAZARD ASSESSMENT
PROBABILISTIC RESPONSE SPECTRA (100, 1,000 AND 10,000 YEAR RETURN PERIODS)



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SULPHUR SPRINGS PROJECT
SEISMIC HAZARD ASSESSMENT
PROBABILISTIC RESPONSE SPECTRUM (2,500 YEAR RETURN PERIOD)

Ref: PE801-00300 M17007
Figure 4.2