

Application of Tectonic Geomorphology in Earthquake Hazard Assessments

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Abstract

Identification of earthquake sources is essential in earthquake hazard assessments. Ideally, earthquake sources should be identified by using a multidisciplinary approach that includes analysis of detailed seismological, paleoseismological, neotectonic, structural, and geophysical data. However, in many cases the required information is not readily available and the evaluation of seismic sources largely relies on the location of recorded earthquake activity.

Tectonic geomorphology (ground surface evidence of tectonic and earthquake deformation) can be used to help to identify earthquake sources. Tectonic geomorphology is a relatively inexpensive tool to improve the knowledge of earthquake hazard.

This paper illustrates the use of tectonic geomorphology for site specific earthquake hazard assessments in three case studies from different tectonic regions namely, Papua New Guinea, New Zealand and Western Australia. Tectonic geomorphology was used in these regions to:

- Recognise potential active faults and estimate associated earthquake magnitudes.
- Improve the selection of earthquake time histories used in dynamic analysis.
- Assess surface deformation associated with blind faults.
- Identify subtle tectonic deformation in areas of low seismicity.

Keywords: Tectonic geomorphology, earthquake hazard assessments, identification of earthquake sources, blind faults, river analysis, subtle tectonic deformation.

1. INTRODUCTION

Earthquake hazard assessment requires the identification and characterization of seismic sources. Ideally, multidisciplinary data, including detailed seismological, paleoseismological, neotectonic, structural and geophysical data should be evaluated to identify earthquake sources. In many cases, however, multidisciplinary data is not available and the evaluation of earthquake sources largely relies on the location of recorded earthquake activity.

The identification of earthquakes sources based mainly on recorded seismicity may be considered insufficient because:

- Most seismic sources have recurrence periods much larger than the time covered by the earthquake record, making earthquake activity rates difficult to properly establish.
- Due to the relatively short period of earthquake recording the potential maximum magnitude at a particular earthquake source is unlikely to have been recorded. The estimation of potential maximum magnitudes becomes more critical when long earthquake recurrences are considered and its estimation requires geomorphological constrains.
- Potentially active faults with no recorded activity may be inadvertently excluded from the seismic hazard assessment.

Tectonic geomorphology is the surface evidence of tectonic and earthquake deformation and can be used to help identify and refine the location and characteristics of earthquake sources. This is particularly useful in the early stages of earthquake hazard studies where multidisciplinary data may not be available.

This paper describes three cases where tectonic geomorphology was a useful tool in earthquake hazard assessment in different tectonic environments. The cases illustrate the analysis of tectonic geomorphology on specific studies in Papua New Guinea, New Zealand and Western Australia to:

- Aid identification of earthquake sources by assessing location, geometry, expected maximum magnitudes and type of movement of potentially active faults.
- Improve the selection of earthquake ground acceleration histories by refining the characteristics of the potentially controlling earthquakes.
- Assess surface deformation associated with blind faults, and
- Recognise subtle tectonic deformation in areas of limited or no recorded earthquake activity.

2. CASE A - DYNAMIC SLOPE STABILITY ASSESSMENT, PAPUA NEW GUINEA

A comprehensive dynamic stability analysis was required for a pit slope with catastrophic consequences of failure on Lihir Island (Lihir), Papua New Guinea (PNG, Figure 1A). Tectonic geomorphology was used to refine the selection of earthquake time histories (accelerograms) required for the dynamic stability analysis.

2.1 Lihir Regional Tectonic Setting and Seismic Hazard

Lihir is located in a highly active earthquake region resulting from complex continental collision, subduction and relative motion between numerous local plates. More than 30 earthquakes with magnitudes greater than 7.5 have been recorded in the region since 1900 (Benz et al., 2011).

Large earthquakes in PNG are typically associated with subduction processes but crustal faults have also generated big shallow earthquakes away from the subduction zone. For example, in 2000 a tsunamigenic $M_w 8$ earthquake took place on the Weitin Fault which is located approximately 80 km, southwest of Lihir (Geist and Parsons, 2005; Figure 1A).

Previous regional probabilistic seismic hazard assessments (PSHA) of PNG have been undertaken by several authors (e.g. Anton and Ripper, 1999, Anton and Gibson, 2007, 2008). Most PSHA studies recognise subduction along the New Britain Trench (approximately 200 km from Lihir) and the Weitin Fault as the controlling earthquake sources for Lihir (Figure 1A). However, these assessments do not specifically include information relating to local active faults due to the lack of neotectonic and paleoseismological data.

2.2 Context for Dynamic Slope Stability Assessment

Dynamic stability assessment of the pit slope required earthquake acceleration time histories. Earthquake acceleration time histories representing distant seismic sources were initially selected for the assessment based on the results of the available PSHA.

However, due to the tectonic context of Lihir Island, and because the PSHA studies did not include specific information about local faults, adopting earthquake time histories solely from distant sources might not represent the entire seismic hazard of the site. Consequently, evaluation

of possible earthquake characteristics that could be generated on nearby faults was undertaken for inclusion in the analysis.

Detailed neotectonic and paleoseismological analyses were not permissible in this instance due to time and budget constraints. Tectonic geomorphology was therefore used to estimate the type, location and maximum earthquake magnitude of local faults inferred to be potentially active in lieu of the more detailed analysis.

2.3 Identification of Potentially Active Faults

Potentially active faults on Lihir Island were identified using remote sensing data. Analysis of the tectonic geomorphology of the faults included satellite imagery, Shuttle Radar Topography data (SRTM), ASTER Global digital elevation data and LiDAR images (Figure 1B, 1C). This information was complemented with geophysical, geological and structural data of Lihir Island.

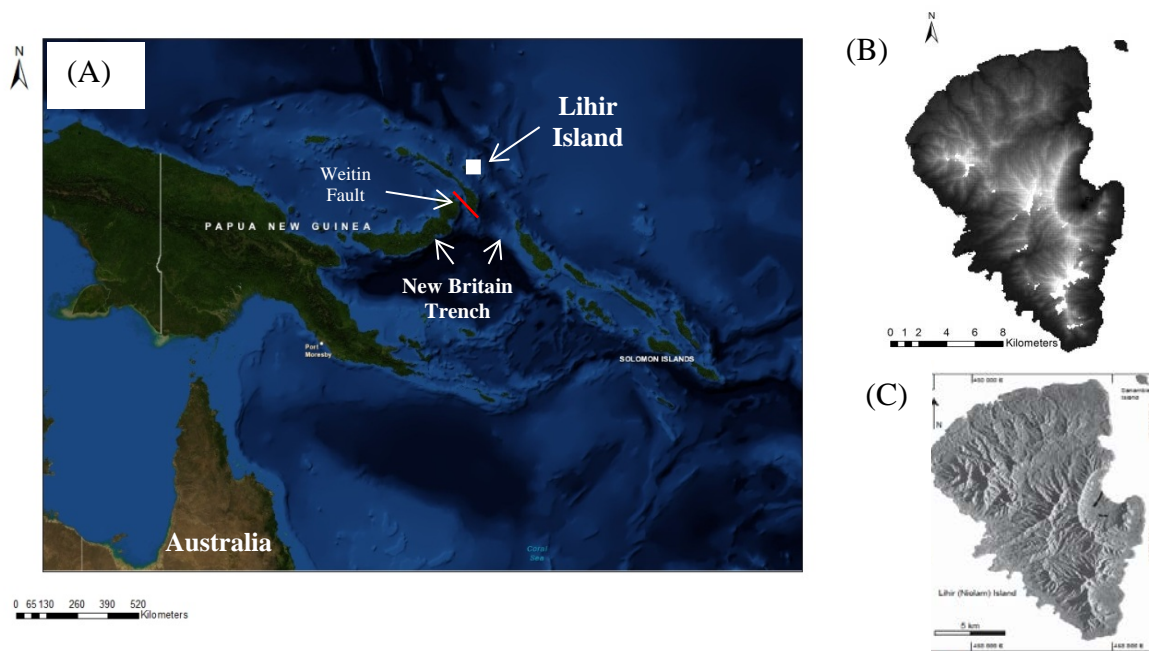


Figure 1. (A). location of Lihir Island, the New Britain Trench and the Weitin Fault. (B) example of SRTM data (from NASA), and (C) DEM data used for analysis of tectonic geomorphology of local faults.

Geomorphological features used to infer potentially active faults included: (i) well defined lineaments, (ii) defined breaks in slope, (iii) linear ridges and/or valleys, (iv) drainage disruption, capture or change in direction, (v) triangular facets, and (vi) distinctive geophysical signature.

Structures with the best geomorphological expression, continuity and geophysical signature were inferred as potentially active faults. Six local faults were selected for assessment of associated earthquake scenarios which involved definition of potential maximum magnitudes, type of faulting and distance from the site (Figure 2). The following was considered for the evaluation of the earthquake scenarios:

- Total length of the fault/segment: this was measured from the geomorphological expression and was assumed to rupture entirely during an earthquake. Faults were segmented only when significant changes in strike were observed.
- Maximum potential earthquake magnitudes: this was estimated using the fault length, fault area and empirical earthquake scaling relationships developed by Wells and Coppersmith (1994) and Wesnousky (2008). Fault area was calculated using the fault length, fault dip and

depth of the seismogenic layer. The depth of the seismogenic layer was assumed from geophysical data to be 15 km.

- Strike-slip or normal displacement faulting: these faulting types were selected from field observations and the current extensional tectonic setting of the Lihir region (Lindley, 2006). Fault dips of 45° and 60° were assumed for normal displacement (based on field observations). The dip on strike-slip faults was assumed to be sub-vertical (85°).

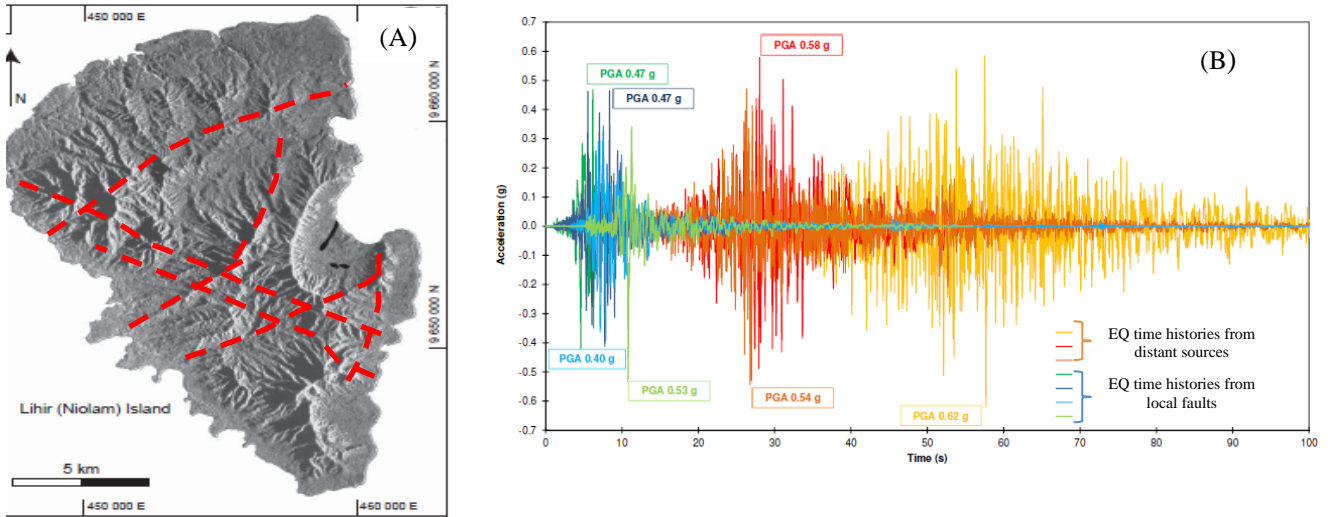


Figure 2. (A) Six local faults selected for estimation of earthquake scenarios (dashed red lines). (B) Comparison of earthquake acceleration time histories from distant earthquake sources (red, orange and yellow - determined from previous PSHA and assumed to represent earthquakes assessed with 10,000 years return period) and local faults (blue and green-this study).

Table 1 shows examples of fault parameters and the average estimated maximum earthquake magnitudes for the six potentially active local faults recognised at Lihir.

TABLE 1
EXAMPLES OF ESTIMATED EARTHQUAKE SCENARIOS

FAULT	LENGTH (KM)	TYPE OF MOVEMENT	DIP (DEGREES)	ESTIMATED MAXIMUM MAGNITUDE (M_w) ¹
F1	11.8	Normal/Strike slip	45/60/85	6.4
F2	4.4	Normal/Strike slip	45/60/85	6.0
F3	9	Normal/Strike slip	45/60/85	6.3
F4	15	Normal/Strike slip	45/60/85	6.4
F5	5	Normal/Strike slip	45/60/85	6.3
F6	3	Normal/Strike slip	45/60/85	5.9

¹ Average maximum magnitude estimated using empirical scaling equations based on fault parameters.

2.4 Earthquake Acceleration Time Histories

In order to incorporate the local fault earthquake scenarios in the dynamic stability analysis, the response spectrum for each earthquake scenario was developed and used to select corresponding earthquake time histories. This involved:

- Estimating peak ground acceleration (PGA) and response spectrum for each local fault using the 2008 Next Generation Ground Motion Prediction Equations (NGA GMPE – Abrahamson and Silva, 2008; Boore and Atkinson, 2008; Campbell and Bozorgnia, 2008; Chiou and Youngs, 2008 and Idriss, 2008) in lieu of prediction equations developed from local data. The PGA value and response spectrum corresponding to the mean value plus one standard deviation were selected for each local fault.
- Comparing (matching) each scenario response spectrum with response spectra from earthquake ground motions from online databases (i.e. PEER and COSMOS). Care was taken to compare earthquakes with similar characteristics to those estimated for the local faults.

Figure 2B compares earthquake ground motions derived from local faults to ground motions from distant sources (assumed to represent the assessed 10,000 year return period earthquake from previous PSHA). The resulting earthquake ground motions from the local earthquake scenarios were subsequently incorporated in the dynamic slope analysis. Inclusion of earthquake ground motions from local structures expanded the range of frequencies and amplitudes used for the dynamic stability analysis.

As a result of the analysis, the final pit was designed to withstand both the earthquake ground motions from local and distant sources.

3. CASE B – IDENTIFICATION OF BLIND FAULTS, NEW ZEALAND

The devastating series of earthquakes between 2010 and 2011 in Christchurch, New Zealand, which resulted in the death of nearly 200 people, occurred on faults that had not been previously recognised. Prior to the earthquakes, the causative faults were not evident from the surface geology in the Canterbury Plains, where Christchurch is located (Figure 3A). These events demonstrated the destructive potential of faults lacking geomorphological expression or faults not reaching the surface (blind faults).

Prior to the Christchurch earthquakes, a blind fault (Springbank Fault) was discovered approximately 30 km northwest of Christchurch by seismic reflection surveys for petroleum exploration. The geophysical data showed that the Springbank Fault does not rupture the surface and as a result, there is no clear geomorphological evidence of its existence (Figure 3B). Tectonic geomorphology was therefore used to infer fault characteristics such as length, position, orientation and potential maximum magnitude.

3.1 Tectonic Setting of New Zealand

New Zealand is located at the boundary between the Australian and Pacific plates. Motion between these plates forms an opposite dipping and obliquely convergent subduction zone. Development of the Southern Alps in the western region of the South Island is attributed to and accommodates the plate motion.

The Canterbury Plains are located east of the Southern Alps and comprise a thick sequence of unconsolidated predominantly sandy gravel deposits of Quaternary age. The deposits have formed by aggradation from rivers draining from the Southern Alps (Cowan et al., 1996; Pettinga et al., 2001).

3.2 Springbank Fault Tectonic Geomorphology

The seismic survey that identified the Springbank Fault suggests that the fault dips approximately 60° to the northwest and that it does not break into the top reflectors of the seismic profile (Figure

3B). The seismic survey however does not provide any information about fault extension or location beyond the seismic survey location.

Quaternary deposits overlying the tip of the Springbank Fault near the surface have been broadly folded in response to reverse-slip movement along the fault plane. According to Suggate (1990), the age of the folded strata ranges from recent to 70,000 years. From results of the seismic survey and the deformation of recent overlying sediments, the Springbank Fault is classified as an active blind thrust that may represent a significant earthquake hazard to Christchurch. Due to its active status, it was considered necessary to assess the fault characteristics to estimate the potential maximum magnitude earthquake and the hazard imposed to the city.

Following the identification of the fault, a higher topographical surface close to the seismic survey location was recognised during fieldwork as the best geomorphological expression of the Springbank Fault (Figure 3C). This surface had been previously interpreted as a glacial aggradation surface but it was later recognised as the surface expression of the Springbank Fault propagation fold (Campbell et al., 2000). Apart from the subtle folding associated with the propagation fold, there was no other clear evidence of the fault at the surface.

3.3 Using River Analysis to Infer the Springbank Fault Location

Because of the lack of evident surface fault expression, the characteristics of nearby rivers were used to infer the location and extent of the Springbank Fault. Rivers can be a useful indicator of tectonic deformation because of their sensitivity to subtle changes along their channel. Tectonic disruption to drainage can take the form of anomalies in the longitudinal river profile, changes in channel direction, changes in sinuosity or channel bed incision, and aggradation or degradation processes. River changes or “anomalies” can suggest the presence of underlying structures that may not be obvious on the surface.

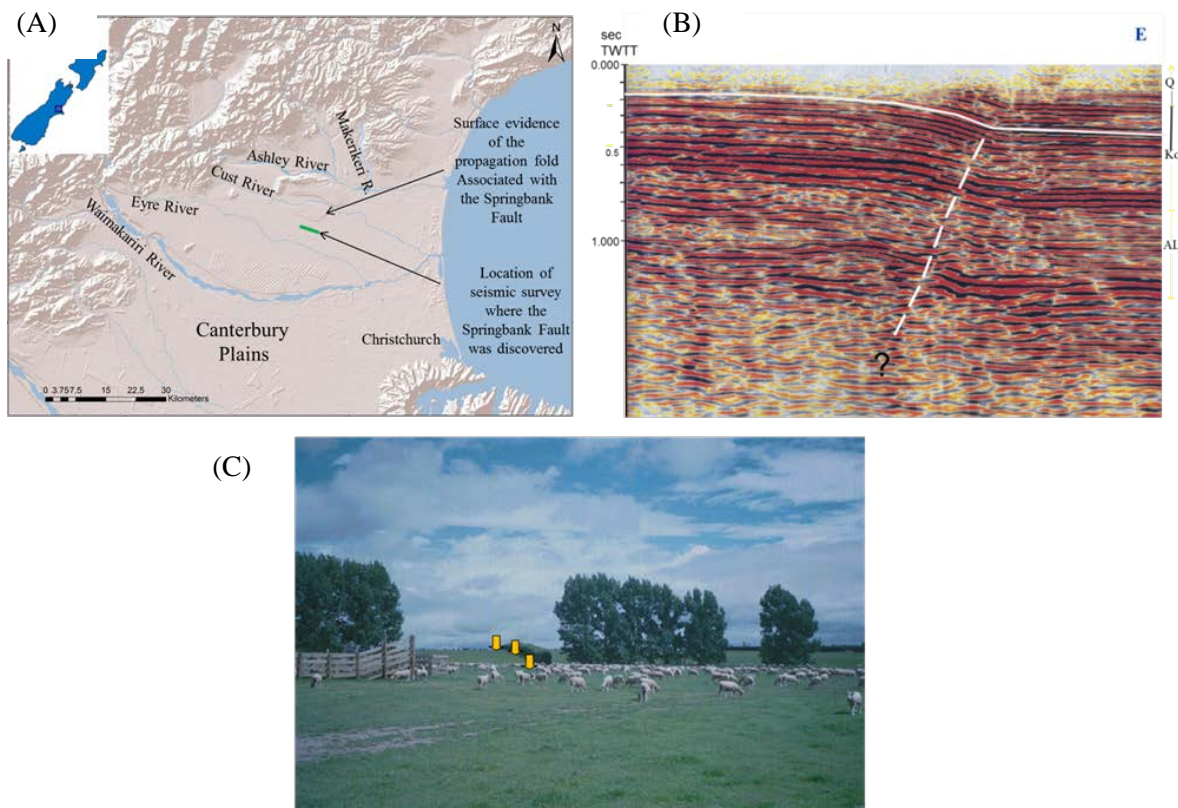


Figure 3. (A) Location where the Springbank Fault was discovered from a seismic survey and primary rivers (Canterbury Plains). (B) Seismic survey showing the inferred Springbank Fault (dashed white line) and associated strata deformation (solid white line - Campbell et al., 2000). (C) Geomorphological expression of Springbank Fault propagation fold (yellow arrows).

Rivers in equilibrium generally develop a smooth-changing, concave longitudinal profile that is assumed to approximate a single exponential curve (Figure 4). Changes from this ideal shape can reflect variations in the lithology along the river bed or tectonic perturbations (Keller and Pinter, 1999; Schumm et al., 2000; Burbank and Anderson, 2011). Because rivers located on the Canterbury Plains drain over thick and relatively uniform sequences of sandy gravel, river anomalies are likely to be a response to tectonic deformation.

River anomalies can be directly measured using the ratio between the stream-gradient index (GI) measured at each river reach (Hack, 1973), and the gradient index (K) of the entire profile. Figure 4 shows how GI and K are measured.

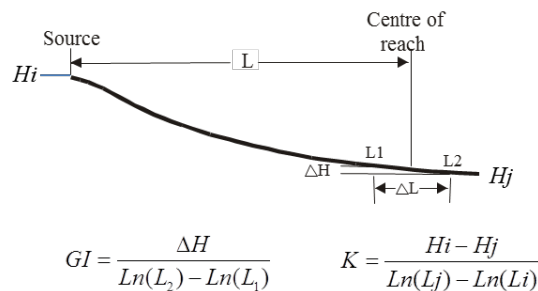


Figure 4: Example of river longitudinal parameters used in calculation of GI and K (Hack 1973).

GI/K ratios close to one indicate a river profile close to the ideal shape expected for rivers in equilibrium. Anomalies in the measured longitudinal profile are expressed as very low ($GI/K < 0.3$) or high ratio values ($GI/K > 2$).

To infer the location of the Springbank Fault from river analysis, the following steps were undertaken:

- Rivers draining through the project area selected for analysis included the Cust, Eyre, Waimakariri, Ashley and Waikerikeri Rivers (Figure 3A).
- Because the Cust River was recognised as flowing directly across the Springbank Fault and associated fold as identified from geophysics and field work, it was selected as the basis for the river profile analysis.
- The Cust River has a high GI/K ratio (4.2) where it crosses the known location of the Springbank Fault (Figure 5). Additionally, the river changes from a meandering pattern to one of multiple channels (anastomosing pattern), increases incision across the fault and associated fold and increases sinuosity after crossing the fold.
- The behavior of the Cust River across the Springbank Fault and associated fold was compared with other rivers in the area to infer the presence of the Springbank Fault.
- Locations where rivers displayed anomalous characteristics, such as anomalous longitudinal profiles, changes in sinuosity or channel width, were compared with geological maps and available tectonic/structural information.

3.4 Results of the River Analysis

Figure 5 shows the GI/K ratios along the profile of the Cust, Eyre, Ashley Waimakariri and Waikerikeri Rivers together with the location of previously known structures. In most cases, changes in river characteristics are directly associated with recognised faults or folds and have $GI/K \geq 2$. In some instances, changes in river characteristics were not explained by changes in lithology or known structures. It is therefore considered possible that these changes are attributed to tectonic deformation associated with unmapped tectonic structures.

Similar changes to those observed along the Cust River in relation to the known location of the Springbank Fault and associated uplift are observed along the Ashley and Eyre Rivers to the north and south of the Cust River, respectively (Figure 5). River changes include alteration in river pattern and high GI/K ratios (>3) (Figure 5). These river anomalies are not associated with any known structures but are coincident with an extension of the Springbank Fault from its known position near the Cust River.

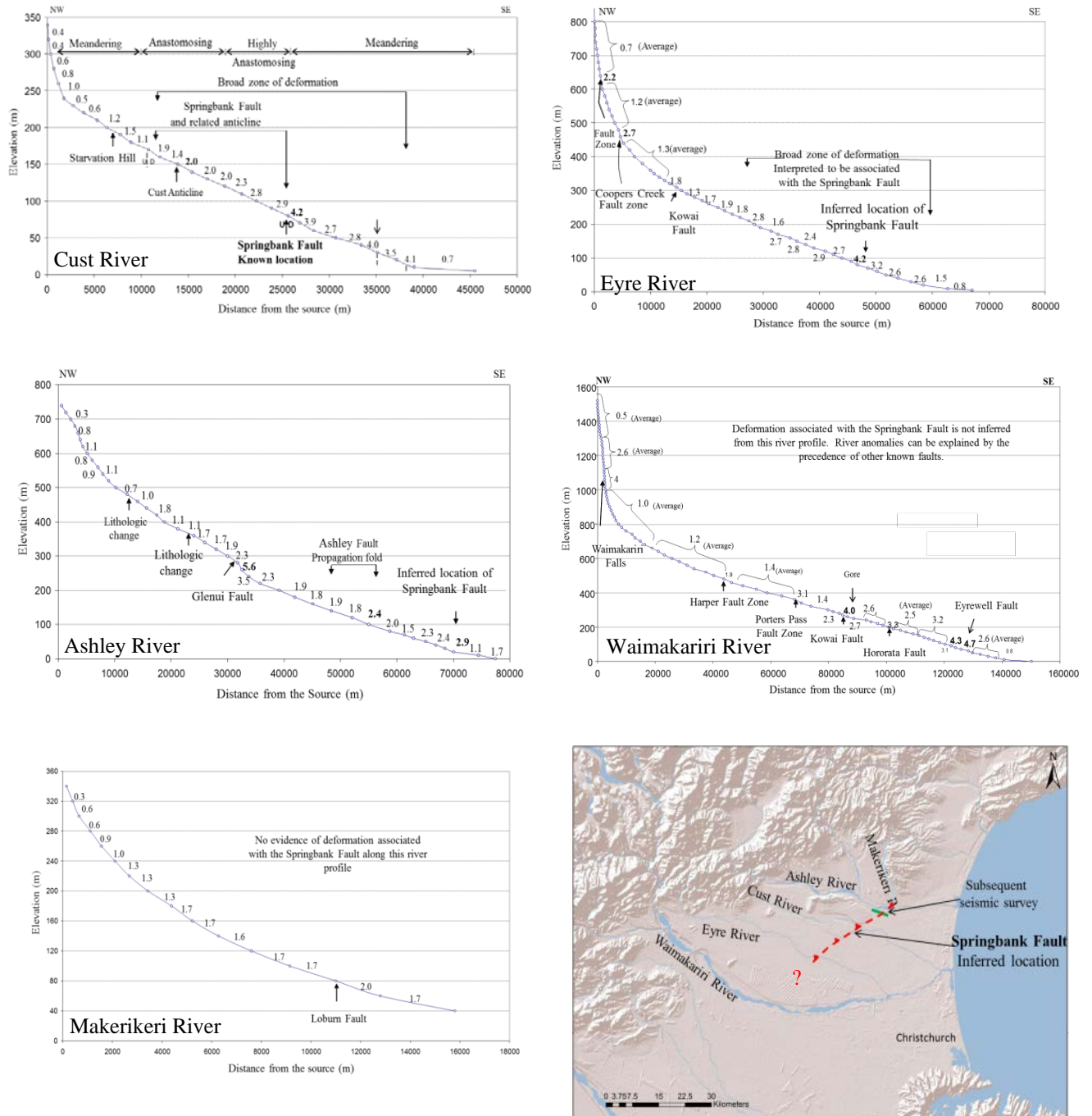


Figure 5. River longitudinal profiles and GI/K ratios along the Cust, Eyre, Ashley, Waimakariri and Makerikeri Rivers. The location of the rivers and the inferred location of the Springbank Fault from the river analyses are also shown (lower right).

Due to the similarity of the changes experienced by the Ashley, Eyre and Cust Rivers, the changes in river characteristics were interpreted to be a response to deformation arising from the underlying Springbank Fault. Similarly, the Springbank Fault was interpreted to terminate before

reaching the Waimakariri and Makerikeri Rivers located to the south and north of the Cust River, respectively, because there was no evidence of deformation along the projected continuation of the Springbank Fault underneath their channels (Figure 5).

The following was inferred from the analysis of tectonic geomorphology and the specific river response to the Springbank Fault:

- The fault is a reverse/thrust structure extending for approximately 26 km between the Ashley River and the Eyre River.
- The structure is associated with a broad anticline with maximum topographical expression close to the central section of the fault where maximum fault displacement is expected (based on theories of fault growth; Burbank and Anderson, 2011).
- A maximum potential magnitude $M_w 6.7$ is estimated for the Springbank Fault based on empirical relationships developed by Wells and Coppersmith (1994), Stirling et al. (2002) and Wesnousky (2008).

The location of the Springbank Fault inferred from the river analysis was confirmed by subsequent seismic surveys (Figure 6). Tectonic geomorphology, and specifically in this case river analysis, was an effective tool to infer tectonic deformation associated with a blind fault where surface expression of faulting is not evident.

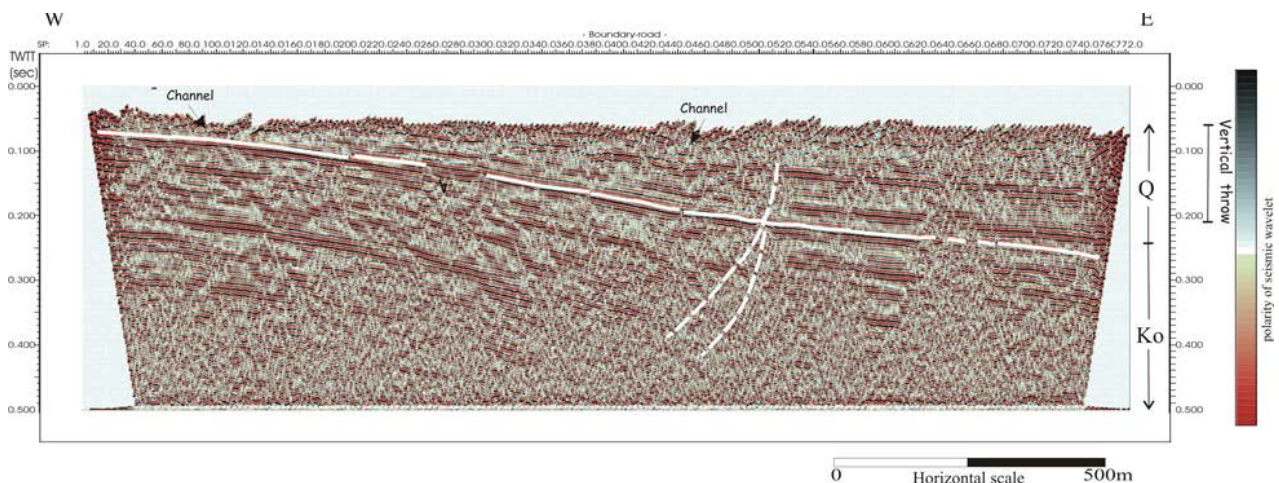


Figure 6. Example of a seismic profile which confirmed the location of the Springbank Fault (dashed white line) and associated deformation (white line) inferred from river analysis. The location of the profile is shown in Figure 5.

4. CASE C - UPLIFT DEFORMATION, WESTERN AUSTRALIA

The southern coastal margin of Western Australia (WA) is classified as a stable continental region. The area is located away from plate tectonic boundaries and has low seismicity. It has been suggested that, despite its classification as a stable continental region, the southern margin of WA has experienced significant uplift since the Neogene (Sandiford, 2007). Tectonic geomorphology and river analysis were used as tools to recognise tectonic uplift in the region.

4.1 Tectonic Setting

The southern coastal margin of WA formed when Australia separated from Antarctica during the Cretaceous break-up of the supercontinent Gondwana (Li and Powell, 2001). The geology of the region is dominated by the Archaean Yilgarn Craton and the Proterozoic Albany-Fraser Orogen (Figure 7).

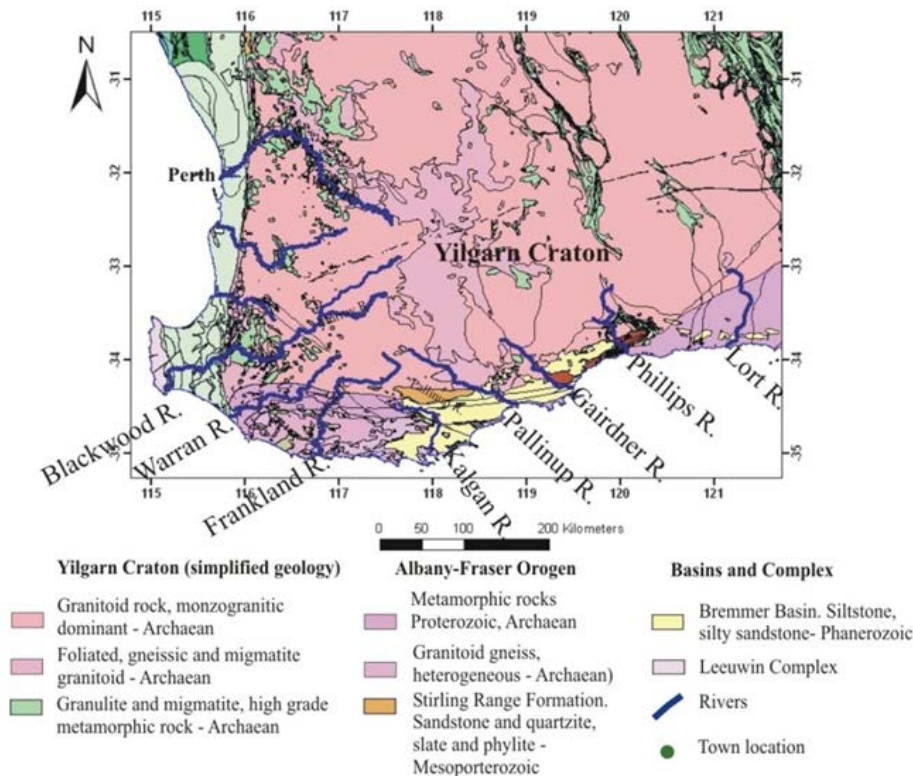


Figure 7. Location of major rivers and simplified geology of the southern coastal margin of WA (Geological Survey of Western Australia)

4.2 Tectonic Geomorphology and Drainage Analysis

As discussed previously, river characteristics can be used to infer zones of tectonic deformation in cases where there is little surface evidence of deformation. In addition to analysis of river profile response, other river characteristics were examined to infer uplift including (Figure 8):

- **Determination of the slope-area (SA) relationship** (Flint, 1974) expressed as:

$$S = K_s A^{-\theta} \quad (1)$$

Where K_s is the Steepness Index and θ is the Concavity Index.

The slope-area relationship (1) predicts the values of steepness and concavity along a river profile in equilibrium. Concavity values for rivers in equilibrium are expected to be relatively constant along the river profile with values between 0.3 and 1.1 (Sklar and Dietrich, 1998; Snyder et al., 2000).

- **Distance from the divide versus local slope (DS) relationship** (Goldrick and Bishop, 2007).
The DS relationship is used to recognise persistent, steady-state (equilibrium) response to changes in lithology (expressed as a parallel upwards shift in the DS relationship) and disequilibrium response to relative base-level fall associated with uplift (expressed as a well-defined peak in a DS relationship; Goldrick and Bishop, 2007).
- **Changes in river channel direction and increased valley incision.**
River response to uplift may include changes in river direction and increased incision across the uplifted area (Snyder et al., 2000; Kirby and Whipple, 2001; Snyder et al., 2002; Doyle and Harbor, 2003; Wobus et al., 2006).

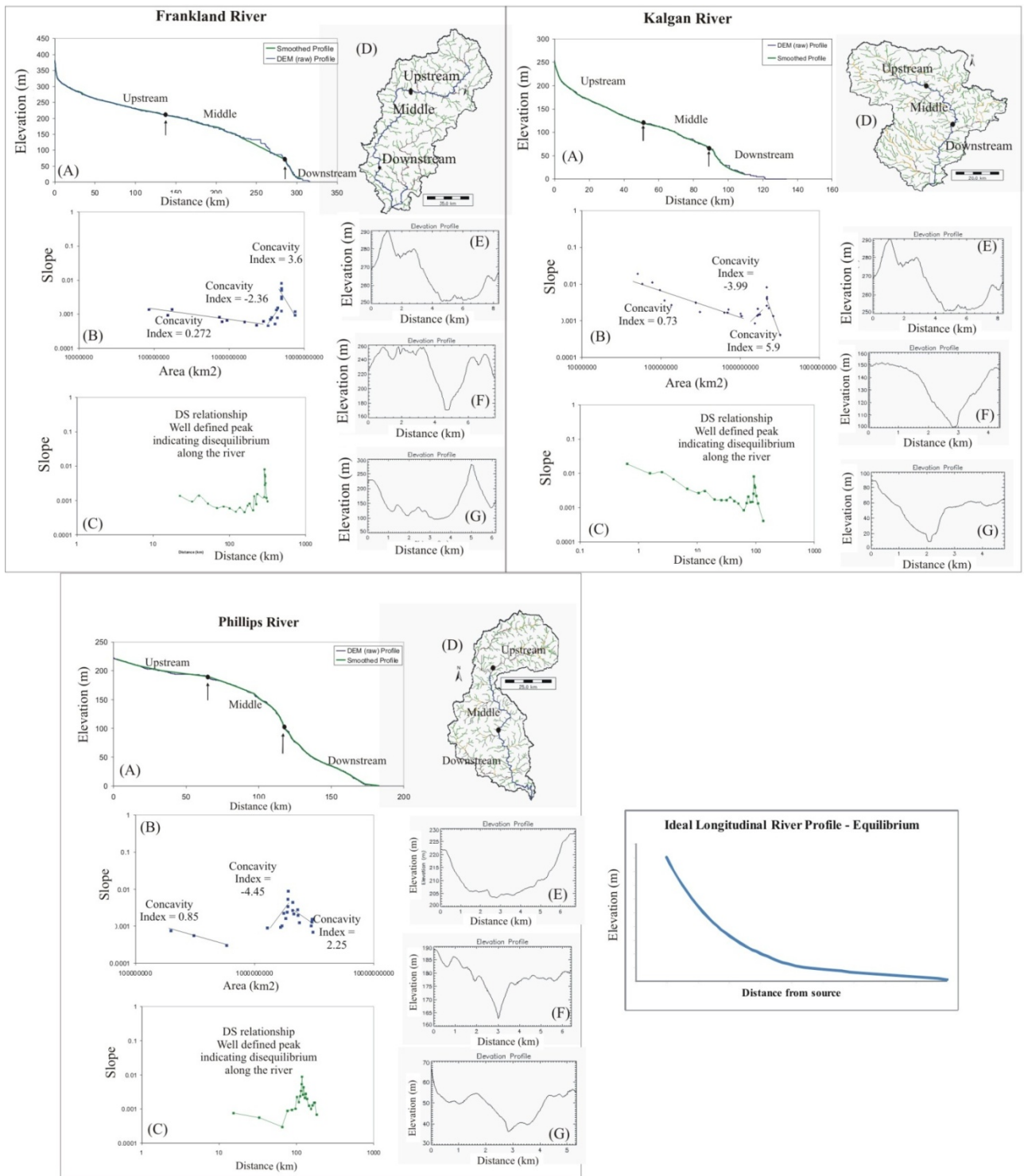


Figure 8. Morphometric analysis along the Frankland River (top left), Kalgan River (top right), and Phillips River (lower left) showing river anomalies. For each river: (A) Longitudinal profile (an ideal longitudinal river profile in equilibrium is also presented for comparison, lower right). Each river profile shows an upstream smoothly changing concave segment, a middle strongly anomalous convex segment and a downstream highly concave segment. (B) SA relationship reflecting the strong concavity variations along each river profile. (C) DS relationship reflecting the strongly-anomalous convex profile with well-defined peaks in the middle river segments. (D) Asymmetric river basin geometry. (E, F and G) River incision at upstream, middle and downstream river sections respectively. For each river, strong increase of river incision occurs in the anomalous convex middle river segments, suggesting river response to uplift.

4.3 Results

10m digital elevation models (DEM) were processed to extract characteristics of the major rivers in the region, including the Blackwood, Frankland, Kalgan, Gairdner, Phillips, and Lort Rivers (Figure 7). Figure 8 shows the longitudinal profiles, SA relationship, DS relationship and river incision of the Frankland, Kalgan and Phillips Rivers.

The data shown in Figure 8 show that most rivers in the south of Western Australia have systematic and consistent anomalies. Most of the analysed rivers have three segments with markedly different characteristics (Figure 8):

- The first (upstream) segments are smooth-changing concave segments with concavity indices varying between 0.2 and 0.8 (Figure 8).
- The second (middle) segments have high negative values of concavity that reflect strong anomalous convexities along the channel.
- The third (downstream) segments have extremely high values of concavity.

The middle and downstream river segments suggest a strong response to disequilibrium conditions along the rivers. In addition, increased river incision, which is a known river response to uplift deformation, has also developed along the middle river segments (Figure 8F).

In most cases, the river anomalies cannot be explained by lithological changes. Therefore, tectonic deformation and uplift appear to be valid explanations. The river characteristics strongly suggest that rivers in the southern coast of WA are affected by and are responding to tectonic uplift. The potential causes and time of the uplift is beyond the scope of this paper but are discussed elsewhere (Estrada et al., in prep). The mechanisms of uplift are considered to potentially influence the earthquake occurrence in the region.

5. CONCLUSIONS

Tectonic geomorphology is a useful tool in earthquake hazard assessments. It can be used to refine the location and characteristics of potential earthquake sources in cases where limited information is available.

Tectonic geomorphology can be applied in different tectonic environments, from highly seismically active areas to stable continental regions. Ideally, the results inferred from tectonic geomorphological analyses should be confirmed by other methods such as geophysics and paleoseismology.

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