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# Tectonic geomorphology and Holocene uplift rates of the Lae Urban Area, Papua New Guinea

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## Abstract

The city of Lae is Papua New Guinea (PNG)'s second largest, and is the home of PNG's largest port. Here, a convergence rate of ~50 mm/yr between the South Bismarck Plate and the Australian Plate is accommodated across the Ramu-Markham Fault Zone (RMFZ). The active structures of the RMFZ are relatively closely spaced to the west of Lae. However, the fault zone bifurcates immediately west of the Lae urban area, with one strand continuing to the east, and a second strand trending southeast through Lae City and connecting to the Markham Trench within the Huon Gulf.

The geomorphology of the Lae region relates to the interaction between riverine (and limited marine) deposition and erosion, and range-building over low-angle thrust faults of the RMFZ. Flights of river terraces imply repeated tectonic uplift events; dating of these terraces will constrain the timing of past earthquakes and associated recurrence intervals. Terrace riser heights are typically on the order of 3 m, indicating causative earthquake events of greater than magnitude 7.

Future work will expose the most recently active fault traces in trenches to assess single event displacements, and extend the study to the RMFZ north of Nadzab Airport. These results will inform a seismic hazard and risk assessment for Lae city and surrounding region.

**Keywords:** seismic hazard, paleoseismology, tectonic geomorphology, Lae, earthquake.

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# 1 Introduction

The Australian Department of Foreign Affairs and Trade is supporting Geoscience Australia, the University of Papua New Guinea, the University of Technology and Morobe Provincial Disaster Office to undertake an earthquake risk assessment for Lae City and surrounding region. Lae is PNGs second largest city (population ~200,000 people, https://lca.gov.pg/about-lca/), its largest industrial hub, and home of the country's largest port. It also has some of the highest seismic hazard in the country (Ghasemi *et al.*, 2020). Data collection for the assessment includes geodetic, earthquake geology, site response, and building vulnerability components. This paper reports on the preliminary findings of the earthquake geology component, involving mapping of tectonic geomorphology from LiDAR and ALOS Digital Elevation Models (DEMs), and collection of samples for Optically Stimulated Luminescence (OSL) dating.

## 1.1 Tectonic setting

The Finisterre Range and western Solomon Sea of northern Papua New Guinea are the site of a modern arc-continent collision between the West Bismarck volcanic arc (South Bismarck Plate) and the Australian continental margin, along the Ramu-Markham Fault Zone (RMFZ) (Abbott *et al.*, 1994a; Holm *et al.*, 2016) (**Figure 1** - inset). Initial collision of the Finisterre terrane with the continental margin at 3.0-3.7 Ma uplifted Paleogene volcanic rocks (Finisterre Terrane/Volcanics), which were rapidly eroded and deposited as volcano-lithic turbidites (Sukurum and Nariawang units) (Abbott *et al.*, 1994b). Southeast propagation of the collision tip caused incorporation of these rocks into an accretionary wedge. Rapid uplift raised the terrane foreland above sea level sometime after 1.8-1.3 Ma (Crook, 1989a). Fluvial, lacustrine, and marginal-marine deposits (Leron Formation) accumulated in a terrane foreland basin (Markham Basin) that developed south of the collision zone (Abbott *et al.*, 1994b). Further propagation of the thrust front toward the foreland incorporated the Leron Formation into the fold-and-thrust belt. Rapid uplift of the Finisterre Range and voluminous volcano-lithic sedimentation (Markham Formation) continues to the present (Liu, 1993), responding to a contemporary convergence rate of 50 mm/yr (Stanaway *et al.*, 2009). Understanding deformation within the Leron and Markham formations is key to evaluating the contemporary earthquake hazard.

## 1.2 Structural geological setting

Large asymmetrical folds with shorter southern limbs are developed in the Leron Formation, and are generally associated with north to northeast-dipping thrusts (Liu, 1993). A frontal Markham basin-wide (hanging-wall) anticline is associated with the frontal thrust of the RMFZ (Crook, 1989b; Liu, 1993). Twenty kilometres northwest of Lae, the basin-wide anticline splays with one arm trending in an easterly direction and the other to the southeast (**Figure 1**).

The southern boundary of the anticline that continues to the east has been mapped as the Gain Thrust (Abbott *et al.*, 1994a). Another fault has been mapped at the northern margin of the east-trending anticline, and is variably called the Wongat Thrust or Wongat Thrust North (Abbott *et al.*, 1994a). This structure marks the southwest boundary of the significant relief (up to 3-4 km) relating to the Finisterre and Saruwaged ranges. The Gain Thrust is mapped as terminating against the Wongat Thrust approximately 65 km east of Lae shortly after both faults go offshore in the Tamigidu/Ologidu area. Geophysical data indicate that the Wongat Thrust continues some ~100 km offshore before losing displacement ~ 50 km short of the New Britain Trench (Abbott *et al.*, 1994a).

The southeast splay of the anticline which deforms the Leron Formation is expressed topographically as the Atzera Range. In the Lae urban area, alluvium belonging to the Leron and Markham formations is uplifted across the Aztera Range anticline axis (Buleka *et al.*, 1999). The underlying fault continues offshore at the Markham River mouth, to join the RMFZ in the Markham Trench (Abbott *et al.*, 1994a). The RMFZ in the Markham Trench, offshore of Lae, has also been called the Wongat Thrust South (Abbott *et al.*, 1994a; Koulali *et al.*, 2015).

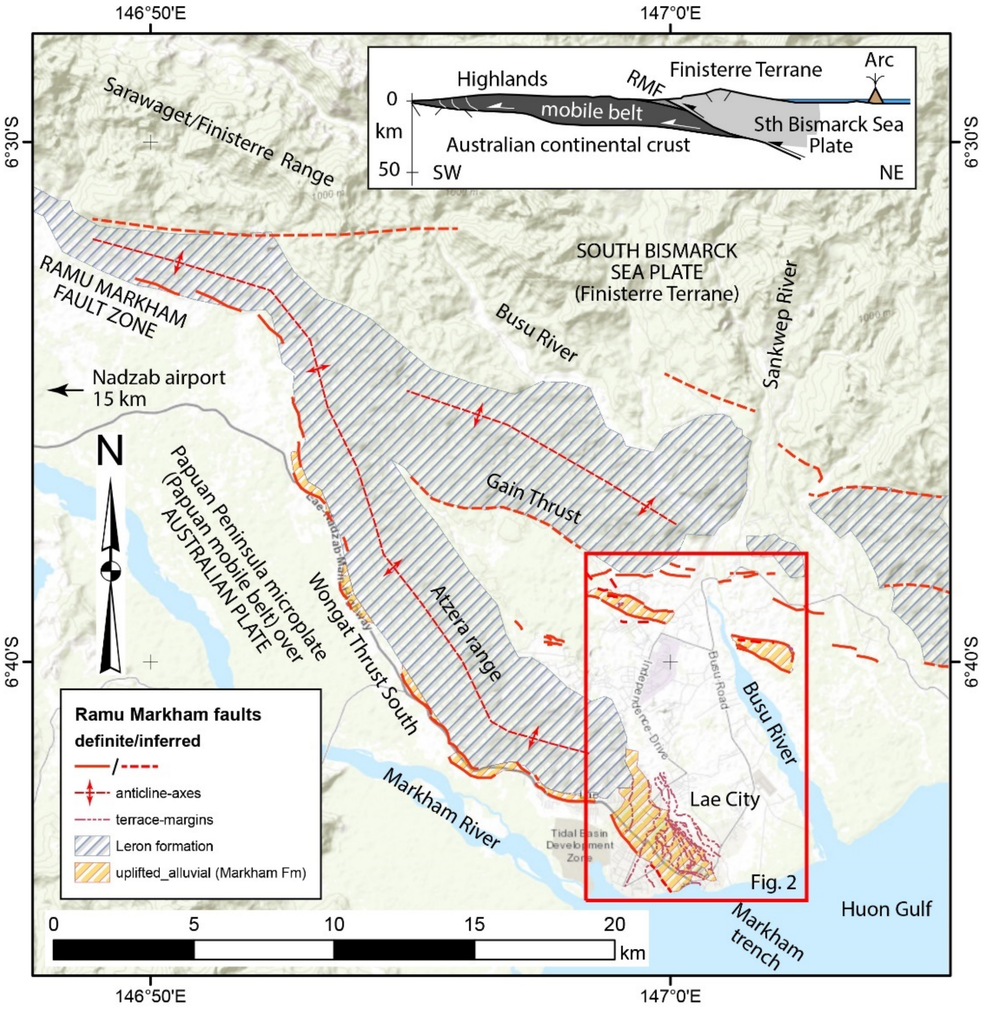

*Figure 1. The Lae Study area with anticlines developed in Leron formation sediments above faults of the Ramu-Markham Fault Zone shown (Crook, 1989b; Liu, 1993; Abbott et al., 1994a). Uplifted Late Pleistocene Markham Formation sediments adjacent to the southern margins of the folds developed in the Leron formation mark the positions of the most recently active thrusts. Inset shows tectonic setting (after Abers and McCaffrey, 1994).*

## 2 Lae earthquake geology study, Phase #1

The geomorphology of the Lae region relates to the interaction between riverine (and limited marine) deposition and erosion, and range-building over low-angle thrust faults of the RMFZ. **Figure 2** shows the extensive alluvial fan deposited by the Busu River over the last several thousand years. Three age-distinct geomorphic levels of fan surface are recognised; the sediments deposited all fall within the definition of the Markham Formation (Late Pleistocene to Holocene). The oldest and steepest fan is associated with high-level terraces along the Sankwep and Busu rivers within the Saruwaged Ranges before emerging at the range front and grading towards the Atzera Range and the coast. The fan is locally deformed at the range front, and across a line parallel to the range front ~1-2 km south. An extensive mid-level fan has deeply incised into the high-level fan and truncates deformation structures developed within it. Sediments relating to the incised fan have been uplifted across a line parallel to the Atzera Range in the Lae urban area. Topographic profiles allow that the mid-level fan may have experienced mild deformation across the frontal thrust of the Gain Thrust, but the deformation is not obvious. The modern fan has incised into the eastern flank of the mid-level fan and appears to be undeformed.

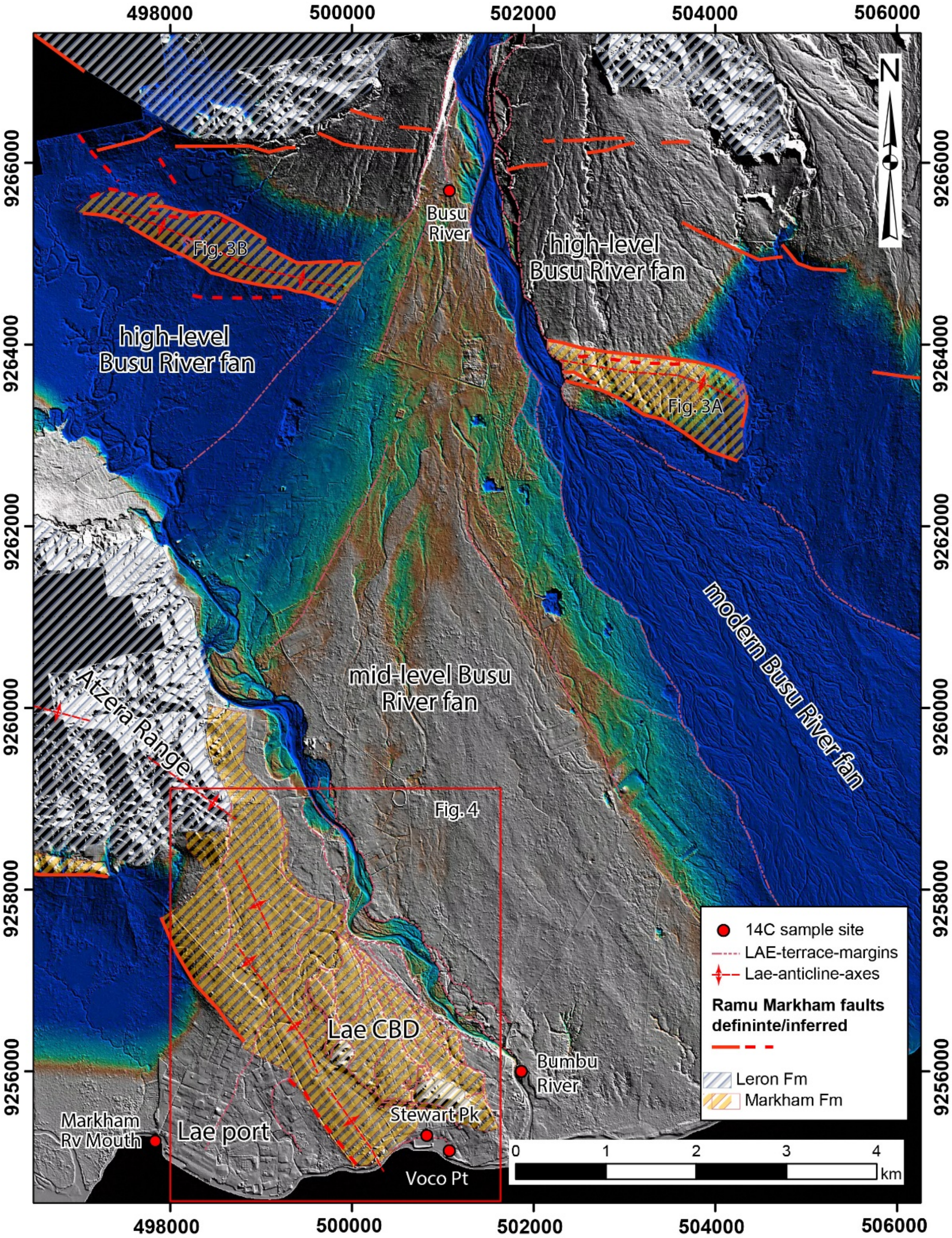

*Figure 2. LiDAR DEM data over the Busu River fan. Colour drape has been tilted northwards to remove the fan gradient. Note that uplifted fluvial surfaces in Lae Urban area occur within the footprint of the Busu River paleo-fan. See Figure 1 for location.*

## 2.1 Tectonic geomorphology related to the most recent events on the Gain Thrust

North of Lae Central Business District (CBD), the Busu River has eroded a broad channel through an anticline perhaps relating to the most recent few large earthquake events on the Gain thrust (**Figures 2 & 3**). Terraces developed where small streams interact with the anticline are consistent with terrace formation as the result of three uplift events. Terrace riser heights are typically on the order of 3 m, indicating causative earthquake events of greater than magnitude 7 (Wells and Coppersmith, 1994) if the terrace risers are tectonic in origin. Samples were taken from deformed fluvial gravels east and west of the Busu River for OSL dating. The results of dating may provide two recurrence intervals on the fault and potentially provide a maximum age constraint for the inset fan, and a minimum age constraint for the high-level fan.

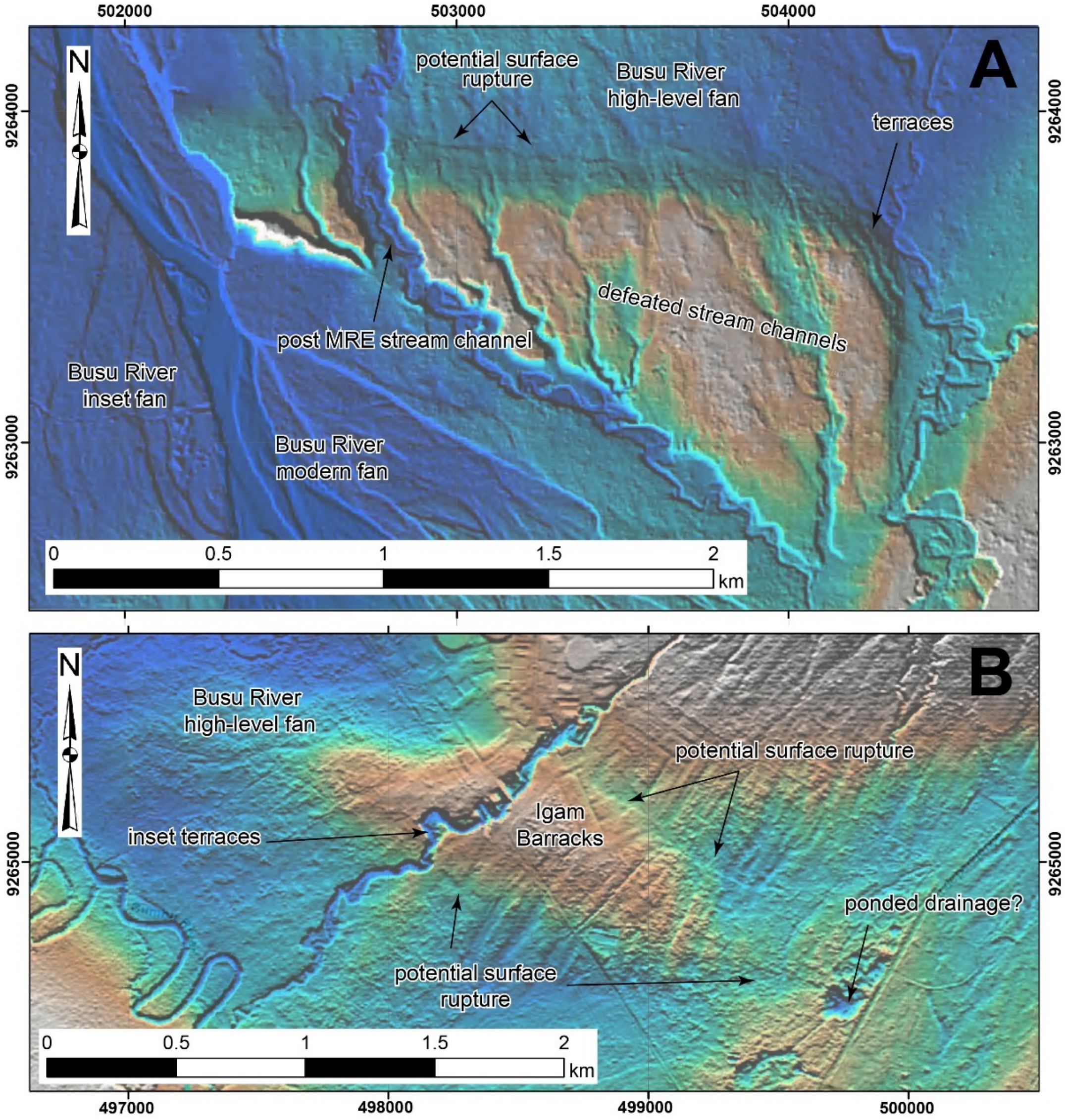

*Figure 3. LiDAR DEM data over a fault-related fold deforming sediments of the high-level Busu River fan. A) fold segment east of the Busu River. B) fold segment west of the Busu River. Colour drape has been tilted northwards to remove the fan gradient. See Figure 2 for location.*

## *2.2 Tectonic geomorphology related to the Wongat South Thrust (Lae urban area)*

Deformation relating to the frontal Wongat South Thrust and hanging wall anticline are evident in uplifted alluvial and marine terraces in the Lae urban area. A flight of eight uplifted and gently folded fluvial surfaces, and two uplifted and folded marine terraces, were mapped using LiDAR digital elevation data (**Figures 2 & 4**). A clear expression of the fault upon which the uplift occurred was mapped striking in a northwest direction between the Lae CBD and the Port Precinct (**Figure 4**). The scarp is 2.5 – 3.0 m high where it crosses Didiyman Creek (1 deformation event), and up to 6.5 m high where it is developed in bracketing paired terrace surfaces ($T_2$, 2 deformation events). Further west, proximal to the Golf Club, the scarp rises to 13.5 m high (4 deformation events?), and is associated with a higher set of paired terraces ($T_3$). The most recent uplift event is indicated by a 2.5 - 3.0 m high scarp developed across the former channel of the Bumbu River (Ch2), now occupied by Didiyman Creek. The Bumbu River is thought to have been diverted to its current location (Ch1) by this event.

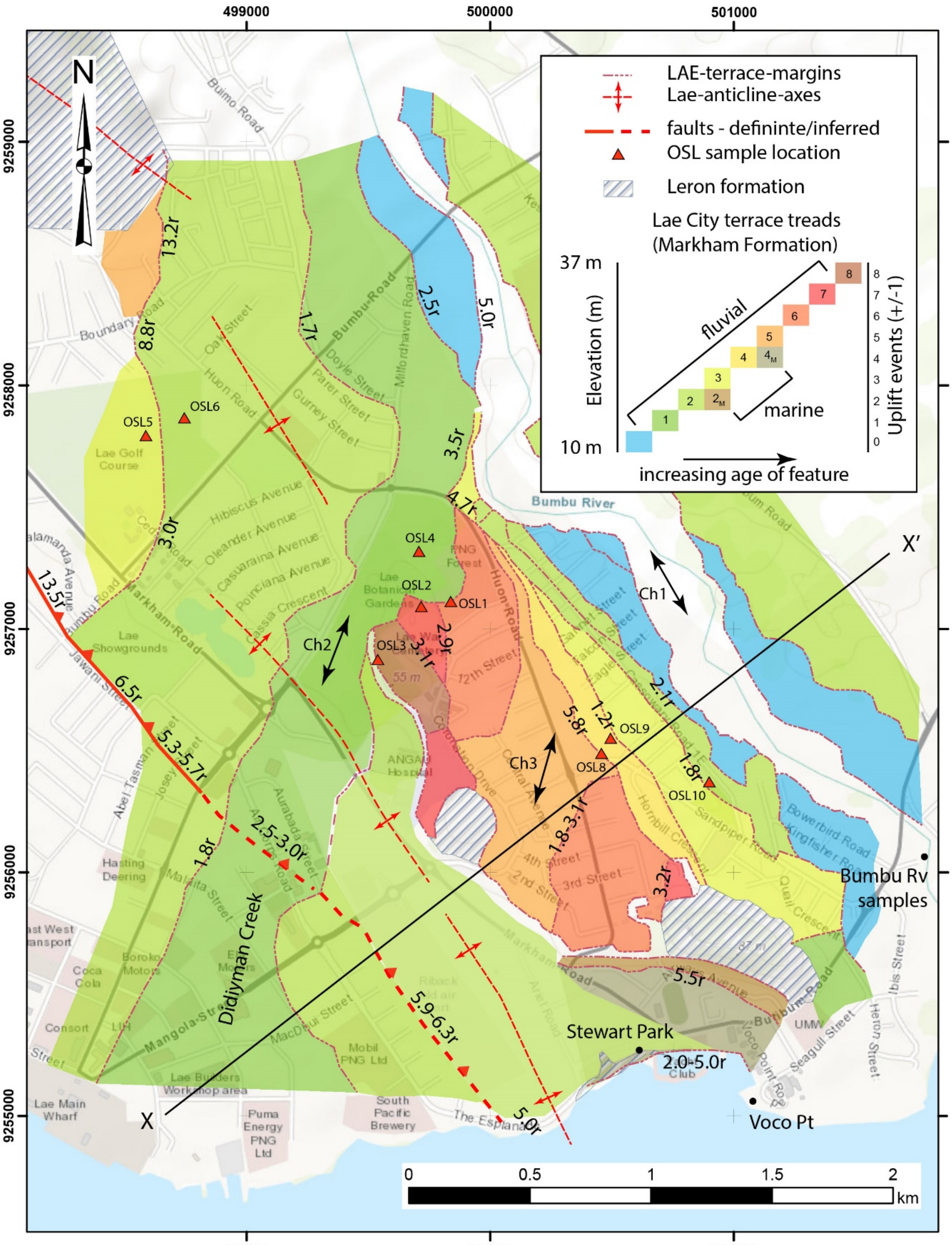

*Figure 4. Lae urban area with terrace treads related to the Bumbu and Busu Rivers marked. Channel-forms are labelled (e,g, Ch1 - Ch3). Anticlines relating to the extension of the Atzera Range anticline are inferred from topographic profiles (e.g. Figure 5). The Ramu-Markham Fault (Wongat South Thrust) may surface rupture northwest of the Lae Showgrounds, but expresses as a fold further east. Terrace elevation with age cartoon in the inset is schematic, and assumes (perhaps implausibly) all terrace elevations are tectonic. Relative heights of terrace risers are labelled with subscript 'r'.*

The Lae CBD is situated on a more elevated abandoned channel (Ch3), also fringed by two higher paired terrace levels. The Lae War Memorial occupies a yet higher terrace remnant. It is unresolved if high-level terraces relate to the Bumbu or Busu Rivers, but regardless their elevation relative to the lower terraces (and perhaps modern river level) may be used to constrain total uplift of these terraces. Three terrace levels carved into the eastern side of the high ground occupied by Top Town are testament to the long-lived impediment to drainage presented by the uplifting Atzera Range (and eastern extension below Lae City). Fluvial sandy gravel samples from various surfaces were taken from shallow hand-excavated pits for OSL dating (**Figure 4**). Dating will help constrain the timing of past earthquakes and associated recurrence intervals.

The relationship of uplifted and folded surfaces to the underlying fault is conceptualised in **Figure 5**. It is clear from this model that the total uplift (and per earthquake event) will vary depending upon proximity to the fault; uplift diminishes over several kilometres to the east. Furthermore, it should be noted that the total vertical displacement at a site comprises a component related to far field uplift across the fault, and a near field component of folding. No interpretation has yet been made as to for non-tectonic terrace riser formation in this preliminary model.

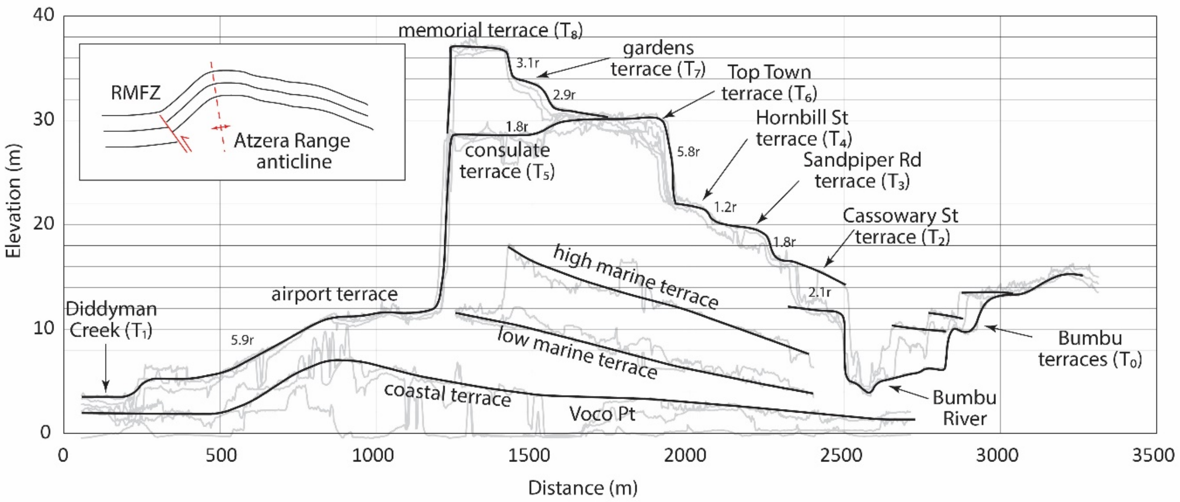

*Figure 5. Composite SW-NE cross section across the Atzera Range anticline, showing the various uplifted fluvial and marine surfaces. The primary profile line is shown as X-X' in Figure 3. Additional sub-parallel profiles were collected across the marine terraces, the War Memorial/Botanical Gardens terraces, and the coastline. Grey lines are Z, Zmax, and Zmin from 100 m wide swath profiles collected using SAGA GIS swath profiling tool through 1 m resolution LiDAR data. Inset shows conceptual model of fold development in the hanging-wall of the fault. Relative terrace riser heights are shown with subscript 'r'.*

# 3 Preliminary conclusions

As yet, we have not received the results of the OSL dating of our samples collected from fluvial terraces. These, and future trenching, will allow us to test our preliminary hypothesis and conceptual model, which simply assumes that all terrace risers are tectonic. However, existing $^{14}$C dating results (Crook, 1989a; Liu, 1993; Buleka *et al.*, 1999) may be assessed within the framework provided by our new tectono-geomorphic conceptual model, and preliminary conclusions made (see **Figure 2** for site locations mentioned below). To facilitate eventual comparison with our OSL ages, and the ages offered by the oral records, the results from previous work have been recalibrated using OxCal (Lienkaemper and Ramsey, 2009), and the average of the age range calculated presented as years before 2023.

Porites corals in growth position from Stewart Park (1-2 m above sea level, ANU-4178, Crook, 1989a; Liu, 1993) and Voco Point (1.5 m above sea level, UtC-7162, Buleka *et al.*, 1999) yield ages of ~1000 years. Liu (1993) suggests that when living these corals would have been situated in 3-5 m of water. This elevation is consistent with the low marine terrace being the shoreline at the time of coral growth (**Figure 5**). The uppermost parts of a peat deposit were accumulating on the western downthrown side of the fault, near the Markham River mouth, coevally (~903 years ago, UtC-7558, Buleka *et al.*, 1999). Coral growth was terminated by deposition of shoreface sands at Stewart Park (~900 years ago, ANU-7585, Crook, 1989a; Liu, 1993), before the site, and the Markham River mouth peat site, were over-run by the alluvial material relating to the airport terrace $T_2$. Accepting the apparent geomorphic continuity between the low marine terrace and the airport terrace surfaces, two seismic events, involving a total of ~6.5 m of uplift at the fault, can be inferred to have occurred in the last ~900 years. Pholad borings containing “sub-tidal to low inter-tidal pholad shells in life position”, one of which was dated to ~465 years ago (ANU-6019, Crook, 1989a; Liu, 1993), potentially indicate a shallowing of water depth consequent of seismic uplift in the interval ~465 – 900 years ago (the penultimate event). Channel sands interpreted to relate to the Bumbu River overly the coralline and shallow marine strata from the same site and are dated to ~476 years ago, supporting this interpretation (ANU-7619, Liu, 1993).

The timing of the most recent event (MRE) on the fault is not well constrained. It is thought that prior to the MRE the Bumbu River occupied a course along the present-day Didiyman Creek, west of the Lae CBD, and that the river was diverted by the MRE. Corroboration is found in the oral traditions of villagers in Bumbu Settlement, at the mouth of the present river, who relate that the river occupied the westerly course "bepo long taim waitman ibin kam", i.e. some time before Europeans came (Liu, 1993). Lui (1993) suggests a tentative age of 250 years ago. We are also aware of a story from Bukawa Village, located near where the Gain Thrust goes offshore, that describes a large earthquake and tsunami “well before [German missionary] Johannes Flierl's time in PNG”, i.e. before 1886. This story notes “I also heard about…the mouth of Bumbu that disappeared due to the tsunami”, and describes the disappearance into the sea of a peninsula that was previously located at Nduc (Cape Arkona), i.e. where the Gain Thrust intersects the coastline. This latter observation may be interpreted to suggest coseismic deformation due to rupture of the Gain Thrust rather than the Wongat South Thrust, and therefore it is unclear if this story refers to the same (multi-fault rupture) event as the story from Bumbu Settlement, or a separate event.

An age of ~1317 years ago was obtained from charcoal from a poorly documented site on the mid-level Busu River fan near to where it emerges from the Saruwaged Range front (UtC-7175, Buleka *et al.*, 1999). A bulk sediment residue sample from the same site (UtcC-7176) obtained an age of ~6429 years ago, which potentially reflect redeposition from the Busu River high-level fan. These ages demonstrate the longevity of river interaction with the sedimentary packages being uplifted across the Atzera Range anticline.

Ages of ~9,000 – 11,000 years were obtained on gently dipping (11° to the northeast) Leron Formation sediments from the Bumbu River east of the Lae CBD (ANU-4169, ANU-4407, ANU-5888, ANU-7042, Crook, 1989a; Liu, 1993). It is difficult to directly compare dips as a measure of age due to the varying curvature of the fold (e.g. **Figure 5**), and an angular unconformity surface separating the Leron Formation from the overlying sediments. However, the most steeply dipping terrace surfaces considered in **Figure 4** dip at 0.5 – 1.0° to the northeast, suggesting relative youth. An important implication is that the higher marine terrace is likely to have formed with mean sea level similar to present (i.e. <7,000 years ago, Lewis *et al.*, 2013).

# 4 Next steps

Completion of OSL dating will allow for validation of our mapping and conceptual model. Specifically, we hope to discriminate between tectonic and non-tectonic terrace risers. An age model will then be used to constrain fault slip rates and estimate earthquake recurrence intervals (**Figures 4 & 5**). These data will form a framework for the interpretation of a paleoseismological trench that we hope to excavate across the Wongat South Thrust in coming months. Trenching will allow more accurate dating of the most recent event(s) and direct measurements of single-event displacements. Future investigations will also examine the older uplift history of the Gain Thrust further upstream on the Busu River, given we anticipate only having captured constraints for the most recent three events in the work presented here.

Further into the future we hope to study the RMFZ west of where it bifurcates. Faulted flights of river terraces fringing the Erap River north of the Nadzab airport are an ideal candidate for dating of uplifted surfaces and paleoseismic trenching. Integration of these data with those from the Lae area will give insights into how the RMFZ behaves as a system and the relative hazard along the different strands of the fault system.

# 5 Acknowledgements

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# 6 References

Abbott, L. D., Silver, E. A., and Galewsky, J. (1994a). Structural evolution of a modern arc-continent collision in Papua New Guinea, Vol 13, No 5, pp 1007-1034, https://doi.org/10.1029/94TC01623.

Abbott, L. D., Silver, E. A., Thompson, P. R., Filewicz, M. V., Schneider, C., and Abdoerrias (1994b). Stratigraphic constraints on the development and timing of arc-continent collision in northern Papua New Guinea, *Journal of Sedimentary Research* Vol 64, No 2b, pp 169-183, https://doi.org/10.1306/D4267F82-2B26-11D7-8648000102C1865D.

Abers, G. A., and McCaffrey, R. (1994). Active arc-continent collision: Earthquakes, gravity anomalies, and fault kinematics in the Huon-Finisterre collision zone, Papua New Guinea, Vol 13, No 2, pp 227-245, https://doi.org/10.1029/93TC02940.

Buleka, J., Prior, D., and Spek, A. V. D. (1999). COASTPLAN - geology and natural hazards of Lae city and surroundings, Papua New Guinea, *Geological Survey Division, Department of Mineral Resources, Papua New Guinea - & - Committee for Coordinating Geoscience Programmes in East and Southeast Asia CCOP*, http://dx.doi.org/10.13140/RG.2.1.2784.8729.

Crook, K. A. W. (1989a). Quaternary uplift rates at a plate boundary, Lae urban area, Papua New Guinea, *Tectonophysics* Vol 163, No 1, pp 105-118, https://doi.org/10.1016/0040-1951(89)90121-2.

Crook, K. A. W. (1989b). Suturing history of an allochthonous terrane at a modern plate boundary traced by flysch-to-molasse facies transitions, *Sedimentary Geology* Vol 61, No 1, pp 49-79, https://doi.org/10.1016/0037-0738(89)90041-9.

Ghasemi, H., Cummins, P., Weatherill, G., McKee, C., Hazelwood, M., and Allen, T. (2020). Seismotectonic model and probabilistic seismic hazard assessment for Papua New Guinea, *Bulletin of Earthquake Engineering* Vol 18, pp 6571-6605.

Holm, R. J., Rosenbaum, G., and Richards, S. W. (2016). Post 8Ma reconstruction of Papua New Guinea and Solomon Islands: Microplate tectonics in a convergent plate boundary setting, *Earth-Science Reviews* Vol 156, pp 66-81, https://doi.org/10.1016/j.earscirev.2016.03.005.

Koulali, A., Tregoning, P., McClusky, S., Stanaway, R., Wallace, L., and Lister, G. (2015). New Insights into the present-day kinematics of the central and western Papua New Guinea from GPS, *Geophysical Journal International* Vol 202, No 2, pp 993-1004, https://doi.org/10.1093/gji/ggv200.

Lewis, S. E., Sloss, C. R., Murray-Wallace, C. V., Woodroffe, C. D., and Smithers, S. G. (2013). Post-glacial sea-level changes around the Australian margin: a review, *Quaternary Science Reviews* Vol 74, pp 115-138, https://doi.org/10.1016/j.quascirev.2012.09.006.

Lienkaemper, J. J., and Ramsey, C. B. (2009). OxCal: Versatile Tool for Developing Paleoearthquake Chronologies - A Primer, *Seismological Research Letters* Vol 80, No 3, pp 431-434, doi: 10.1785/gssrl.80.3.431.

Liu, K. (1993). Sedimentation and tectonics of the Markham Suture, Papua New Guinea, Research School of Earth Sciences. Canberra, Australian National University. **PhD,** 511.

Stanaway, R., Wallace, L., Sombo, Z., Peter, J., Palusi, T., Safomea, B., and Nathan, J. (2009). Lae, a City caught between two plates - 15 years of Deformation Measurements with GPS, 43rd Association of Surveyors PNG Congress, Lae, 12th - 15th August 2009, Focus On Challenges; Society-Space-Surveyors. Lae, PNG, http://www.quickclose.com.au/LaeDeformation.pdf.

Wells, D. L., and Coppersmith, K. J. (1994). New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement, *Bulletin of the Seismological Society of America* Vol 84, No 4, pp 974-1002, http://www.bssaonline.org/cgi/content/abstract/84/4/974