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A GNSS Survey of the Ramu-Markham Fault, Papua New Guinea

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Abstract

The Ramu-Markham Fault (RMF) runs along the northern edge of the Markham Valley in eastern Papua New Guinea's Morobe Province. It is the active plate boundary between the South Bismarck Plate and the New Guinea Highlands/Papuan Peninsula Blocks, and is thought to accommodate about 4 cm/yr of convergence associated with the Finisterre arc-continent collision. Because Papua New Guinea's recently published national seismic hazard map revealed a potential vulnerability of its 2nd largest city, Lae, to RMF earthquakes, Lae has become the focus of a seismic risk study. One of the aims of this study is to improve the characterisation of the earthquake potential along the RMF, and for this reason a new Global Navigation Satellite System (GNSS) campaign has been undertaken to re-survey over 70 existing benchmarks in and around Morobe Province, including about 35 benchmarks in and around the city of Lae itself. The vast majority of these benchmarks have now been surveyed, and in this paper we discuss the survey and a preliminary analysis of the data.

Keywords: GNSS, geodetic survey, Ramu-Markham Fault seismic hazard assessment

1 Introduction

Papua New Guinea (PNG) includes the eastern half of the island of New Guinea, encompassing the transition between the stable continental lithosphere of the Australian landmass and the belt of intense tectonic activity that accommodates its rapid, oblique convergence with the Pacific Plate to the northeast. This tectonic activity is accompanied by a high rate of earthquake occurrence, which has long been recognised as posing a threat to the people and built environment of PNG. For this reason, PNG's current building regulations (Papua New Guinea National Standards Council 1983) include an earthquake loading component that is based on the seismic hazard map of Jury et al., (1982), depicted in Fig. 1a. This map expresses seismic hazard in terms of four zones, within each of which the seismic hazard has a uniform value.

Due to improvements in the coverage of global and regional seismograph networks, the completeness of the earthquake catalogue for PNG has improved dramatically since 1982, and these improvements were used by Ghasemi et al. (2016) as a basis for a Probabilistic

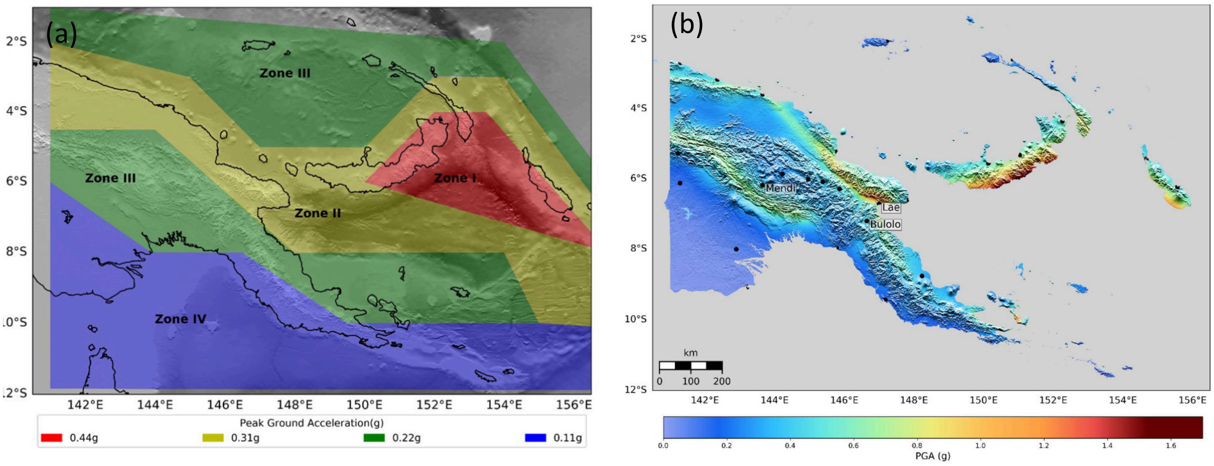

Figure 1. (a) The seismic hazard map of Jury et al. (1982) expressed in terms of 4 zones with uniform hazard levels that were used in PNG's current building regulations. (b) Results of the PSHA of Ghasemi et al. (2020), expressed in Peak Ground Acceleration (PGA) with 10% of exceedance in 50 years.

Seismic Hazard Analysis (PSHA). Further improvements to this hazard assessment were achieved by using tectonic block models obtained from analysis of geodetic data (Wallace et al., 2004 and 2014; Koulali et al., 2015) as well as historical earthquake data to develop a seismotectonic model for PNG that was used to describe the activity of earthquakes above Mw³6.5 (Ghasemi et al. 2020; Fig 1b).

While the early hazard map of Jury et al. (1982) bears some resemblance to the more recent maps of Ghasemi et al. (2016 and 2020), particularly in that the highest levels of hazard are in east New Britain and the lowest in the southwestern part of PNG, the more recent maps show in much more detail the spatial variation of hazard. In particular, some of the highest hazard levels of the Ghasemi et al. (2021) map are near Lae, PNG’s second largest city and home to PNG’s largest port. Building construction in Lae has conformed to the seismic loading standard based on the Jury et al. (1982) hazard levels, but these are much lower than suggested by the 10% in 50 year PGA of the recently developed seismic hazard map, likely resulting in a major vulnerability of Lae’s built environment to earthquakes on the Ramu-Markham Fault (RMF).

Due to the vulnerability in Lae’s built environment suggested by the recent seismic hazard assessment, Geoscience Australia (GA) has partnered with the Government of PNG and academic institutions including the University of Technology at Lae and the University of Papua New Guinea, to assess seismic risk in Lae, in a project funded by the Government of Australia’s Department of Foreign Affairs and Trade. In this paper we discuss a component of this project that uses geodetic measurement of crustal movement to assess strain accumulation along the RMF. The data from this study, along with those of companion studies in earthquake geology (Clark et al., 2023) and building exposure and vulnerability (Mizri et al., 2023), will be used to constrain earthquake scenarios that can be used to assess the potential impacts of future earthquakes near Lae.

2 Tectonic Setting of the Ramu-Markham Fault

The complex tectonics of Papua New Guinea are largely a consequence of the northward movement of the Australian Plate and its oblique convergence with the WNW movement of the Pacific Plate to its north. This convergence is mediated by the rotational and obliquely convergent motions of several microplates (Fig 2.), resulting in a complex tectonic environment that has been the focus of many previous studies – for a recent survey see Baldwin et al. (2012). Within this context, the tectonic event of most concern to this study is the collision of

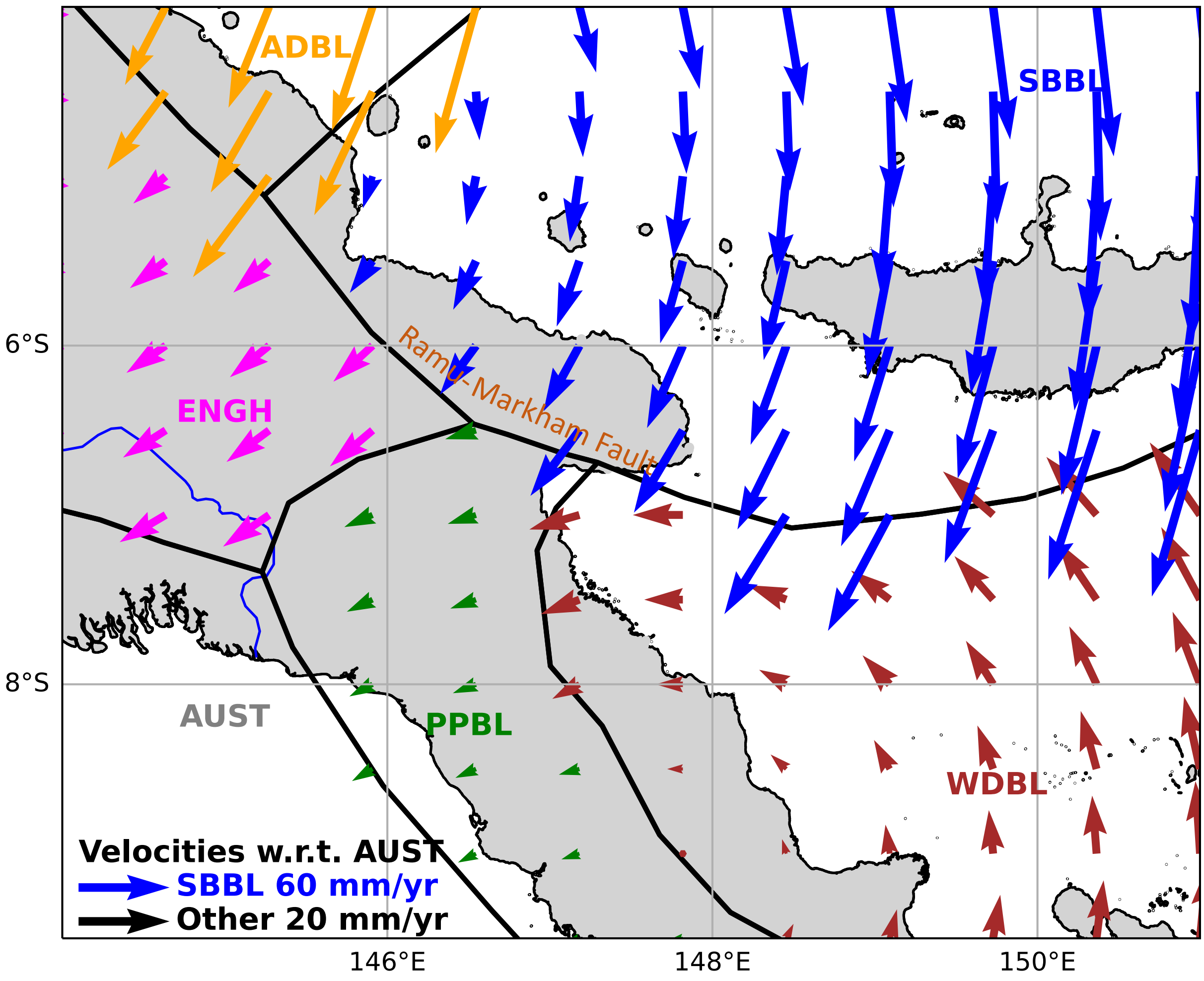

Figure 2. Eastern PNG tectonic blocks and their motions estimated from GNSS studies. The Australian, Adlebert, South Bismark, East New Guinea Highlands, Papuan Peninsula and Woodlark Blocks are denoted by AUST, ADBL, SBBL, ENGH, PPBL and WDBL, respectively. Arrows depict the velocity field relative the AUST based on the tectonic block motion model of Zhao et al. (2023).

the Finisterre Arc with northern New Guinea in the Pliocene (Abbott et al., 1994). This collision is being accommodated along the RMF, as the Finisterre Arc is being accreted to the PNG mainland, creating the Finisterre Range. We have followed previous studies (Silver et al., 1991; Abbott et al., 1994; Wallace et al., 2004; Koulali et al, 2015) in depicting the RMF as connecting with the New Britain Trench off the eastern tip of the Huon Peninsula, and continuing westward to the intersection of the BTF with the New Guinea Trench. The westernmost Solomon Sea Plate is folded along an WNW-ESE axis aligned with and sinking beneath mainland PNG's Ramu-Markham Valley, with a doubly-vergent Wadati-Benioff zone at depths greater than 45 km that is distinct from the shallower seismicity of the RMF (Pegler et al.,1995).

In this study we have adopted the tectonic block model of Zhao et al. (2023), which in PNG is taken from Koulali et al. (2015), and uses data from previous GNSS studies and block model configurations including Wallace et al. (2004 and 2014) and Tregoning et al. (1998). Similar to previous studies (Tregoning et al, 1998; Wallace et al., 2004), Koulali et al. (2015) showed that convergence along the RMF varies from between 5-17 mm/yr west of 146.5° longitude, to as much as 49 mm/yr along the southern margin of the Huon Peninsula at 146.5-148.0° longitude. The high rate of convergence at the eastern end of the RMF is reflected in the uplift of the

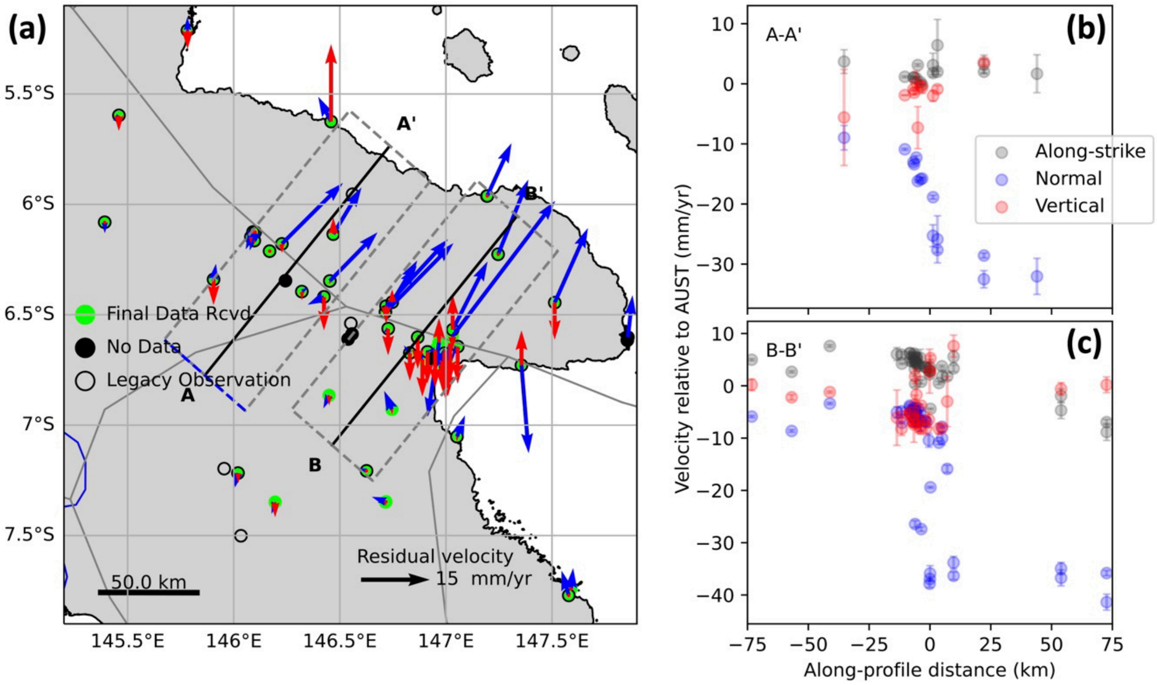

Figure 3. (a) Velocities estimated using data collected in the 2023 and earlier GNSS campaigns. Velocities are expressed relative to the tectonic blocks they are situated on, based on the block model shown in Fig. 2. Blue arrows indicate horizontal velocities and red vertical. (b) and (c) show residual velocities along the profiles A-A' and B-B' in (a), expressed in fault-normal, fault-parallel and vertical components.

Finisterre/Saruwaged Range on the Huon Peninsula (Abbott et al., 1997), which is spectacularly recorded in a set of coral terraces raised up to 1000 m in altitude, some of which have been confirmed as being co-seismic in origin (Ota & Chappell 1999).

3 GNSS Survey

During 2023 GA worked with Quickclose Pty Ltd and the Department of Surveying & Land Studies, PNG University of Technology, to re-survey 64 sites in eastern PNG, focussing particularly on sites near Lae (Fig 3a). GNSS data collected at these sites were used to estimate positions that were combined with estimates from previous surveys to estimate velocities.

The GNSS survey analysis shows general agreement and refinement of previous studies (Wallace et al., 2004; Stanaway et al., 2009 and Koulali et al., 2015). The precision of vertical displacement rates has improved due to the longer time span of observations. The studies generally show rapid convergence across the RMFZ due to the rotation of the SBBL (Fig 2). The Lae urban area is located within the frontal thrust zone with interseismic convergence of ~ 35 mm/yr evident between Hobu primary school and the Lae industrial area. Subsidence of up to 9 mm/yr is observed within the vicinity of the RMFZ with 6-7 mm/yr subsidence evident at all sites within the Lae urban area. Subsidence transitions to uplift of 8 mm/yr at Hobu located North of the Gain and Wongat thrusts. Some of the subsiding sites are located on uplifted terraces and bedrock sites (e.g. Mt Lunaman, Markham Point) so a hydrological cause is not believed to be a significant contributing factor to the observed subsidence. The subsidence is most likely caused by locking of faults within the RMFZ over the geodetic observation period (> 25 years). The geological record suggests long term uplift within the Lae area (Crook, 1989) which is possibly attributable to significant episodic coseismic uplift between longer periods of interseismic subsidence.

Coseismic displacement from the 10 September, 2022 Mw 7.6 normal-faulting earthquake that occurred at 90 km depth beneath the southern flank of the Finisterre Range has also been

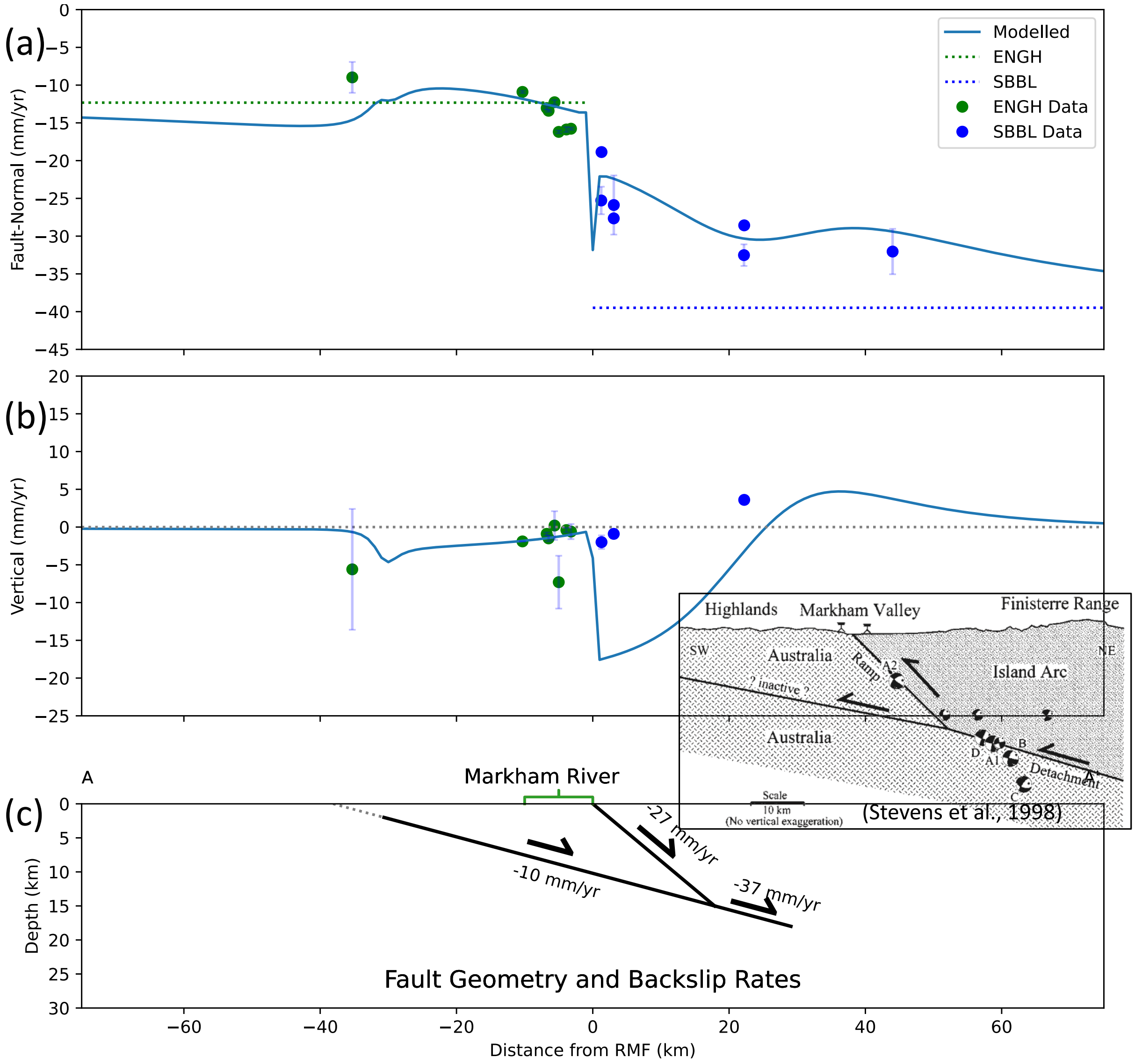

Figure 4. Results of elastic dislocation modelling of the fault-normal and vertical component velocities (w.r.t. AUST) projected onto profile A-A' as depicted in Fig. 3, with the indicated back-slip velocities applied to a shallowly dipping decollement and steeply-dipping ramp fault. The dotted lines in (a) depict the block velocities of ENGH (green) and SBBL (blue) with respect to AUST. The inset shows the fault model of Stevens et al. (1998), from which ours was slightly modified (note that the thrust movement indicated in the model of Stevens et al. (1998) is coseismic, so our model shows interseismic "backslip" in the opposite direction).

observed at a number of geodetic stations with 2-3 cm horizontal displacement and up to 8 cm of vertical displacement. There is also ongoing postseismic displacement observed at the CORS sites at LAE1 and LAE2 at Unitech.

4 Modelling of Ground Movement Due to Fault Locking

Earthquakes occur when there is relative movement between two crustal blocks separated by a fault with stick-slip frictional properties. If the fault were frictionless, the blocks would slide past one another without experiencing any internal deformation, measured velocities will appear exactly as indicated in Fig. 2, and the residuals of those measured velocities with respect to predicted block motions (Fig. 3) should all be within the measurement uncertainty at each site. If this were the case there would be no accumulation of strain energy within each block, and there would be no energy to drive earthquake occurrence. Fig. 3 instead shows a systematic trend of large residuals in fault-normal motion on the northern side of the RMF, which suggests that the hanging wall on SBBL is essentially “locked” to the motion of the blocks on the footwall, ENGH and PPBL in the west and east, respectively. This result is consistent with previous studies (Wallace et al., 2004; Stanaway et al., 2009 and Koulali et al., 2015) and a direct indication that strain is accumulating on the RMF that will eventually be released in an earthquake.

Savage (1983) showed how the motion associated with a locked thrust fault can be expressed as a combination of uniform block motion and a deformation component associated with “back-slip” (relative motion in the opposite direction to long-term slip) applied along the fault surface using elastic dislocation theory. Various geometries have been suggested for the RMF, including a shallowly-dipping fault extending from beneath the Finisterre Range north of Lae to emerge on the surface south of Lae (Wallace et al., 2004), or a more steeply dipping fault that emerges on the surface north of Lae (Koulali et al., 2015). Here we adopt the fault geometry of Stevens et al. (1998), who used a detailed study of the focal mechanisms of the 1993 Kaiapit earthquakes (M_W = 6.4–6.8), to posit the existence of both a shallowly-dipping detachment and a more steeply-dipping ramp fault that emerges north of Lae (Fig. 4). Note, that since there is no evidence for surface faulting south of the Markham River, southward extension of the detachment beyond the river, while it appears to fit the data better, would have to be as a blind thrust that terminates at depth.

Trial-and-error modelling of the backslip on these segments for the profile A-A’ (Fig. 3) shows that this fault model can explain the fault-normal and vertical velocities well, with 27 mm/yr back-slip on the ramp fault, 37 mm/yr back-slip on the detachment beneath the ramp fault, and 10 mm/yr back-slip on the detachment fault up-dip from where it joins the ramp fault. We note that the velocities measured for profile B-B’ in Fig 3 are somewhat more complex (and more crucial for seismic risk in Lae), and interpretation of them is still on-going.

5 Conclusion

In this paper we have discussed the vulnerability of Lae, PNG’s 2nd largest city, to earthquakes suggested by a recent seismotectonic model and associated earthquake hazard map (Ghasemi et al., 2020). Further details into the potential earthquake sources that might affect Lae have been revealed by a Global Navigation Satellite System (GNSS) campaign conducted in 2023, the preliminary results of which have been presented here.

Over 70 geodetic monitoring stations have been re-observed by static GNSS techniques in eastern PNG, at locations extending throughout Morobe and into Madang and Eastern Highlands Provinces, but concentrated in the Lae area. Results of the survey are in overall agreement with previous work, but due to better spatial coverage and longer observation spans, additional detail on locking of the RMFZ west of Lae have been revealed. In particular, subsidence of up to 9 mm/yr is observed at all sites in Lae and the Markham Valley, which is thought to reflect locking of the Ramu-Markham Fault (RMF).

Our preferred model for the RMF involves locking of a steeply-dipping (40°) ramp fault that emerges north of the Markham River and extends to 15 km depth, where it meets a shallowly-dipping (15°) mid-crustal detachment that is also locked - very similar to the model of (Stevens et al, 1998). These require back-slip rates of 27 and 37 mm/yr, respectively. In addition, we find that the detachment extending further southward is also locked at depths shallower than 15 km, with a lower back-slip velocity of 10 mm/yr.

In future work we hope to combine these results with information from geologic surveys (Clark et al., 2023), site response and building exposure (Mirzi et al., 2023) to develop credible scenarios of earthquake impact that can form the basis of a probabilistic seismic risk assessment for Lae.

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